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Research article

Research on the evolution mechanism of intelligent manufacturing transformation of Chinese pharmaceutical manufacturing enterprises based on system dynamics

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ABSTRACT

Under the impetus of the new industrial revolution, how to realize intelligent manufacturing transformation of traditional pharmaceutical manufacturing enterprises has realistic urgency. The study starts from the perspective of complex adaptive system, constructs a system dynamics model of the evolution mechanism of intelligent manufacturing transformation of pharmaceutical manufacturing enterprises based on technological adaptation and evolutionary adaptation, and analyzes it by simulation using Vensim PLE software. The results of the study show that pharmaceutical manufacturing enterprises utilize technological affordances to provide support to realize network product-based manufacturing capability and smart product-based manufacturing capability through technological innovation capability and institutional optimization capability; the technological affordances environment promotes the realization of intelligent manufacturing transformation of pharmaceutical manufacturing enterprises to present a stage transformation law. The study enriches and extends the research paradigm of intelligent manufacturing transformation, and provides a reference for pharmaceutical manufacturing enterprises to realize intelligent manufacturing transformation.

1. Introduction

Driven by the new round of global scientific and technological revolution and industrial revolution, more and more enterprises are improving their ability to cope with uncertainty by choosing appropriate intelligent manufacturing transformation paths to enhance their competitive advantages and thus obtain more resources [1]. The intelligent manufacturing transformation path clarifies the process of creating new value with new logic and resource utilization by enterprises, which in essence helps manufacturing enterprises to choose a path that is most suitable for the long-term development of enterprises in optimizing and restructuring resources [2,3]. In this selection process, enterprises must identify their interconnections with the intelligent manufacturing transformation and the key core elements for achieving a successful intelligent manufacturing transformation [4]. With the accelerated evolution of the new technological revolution characterized by "intelligence", intelligent manufacturing has become the key to high-quality economic

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development [5]. The traditional manufacturing rules and business competitive environment of the past are quietly changing, and the competitive relationship between enterprises has shifted from traditional cost and industry competition to smart manufacturing ecosystem competition [6], with more and more enterprises attempting to gain a sustainable competitive advantage through intelligent manufacturing transformation [7,8]. Under the current fierce competitive pressure, it is particularly important for traditional manufacturing enterprises to explore intelligent manufacturing paths and methods that are suitable for their own long-term development.

In addition, the complex and changing external environment and various emergencies bring more pressure and uncertainty to the survival of enterprises [9]. The global outbreak of COVID-19 has had a huge impact on the real economy and brought incalculable damage to the world economic system [10]. The manufacturing sector was also greatly affected, with several manufacturing enterprises struggling or even heading towards bankruptcy [11,12], testing the viability of manufacturing enterprises. The impact of the epidemic on China's manufacturing industry reflects the fact that most manufacturing enterprises, especially small and medium-sized process manufacturing enterprises, have a low level of automation and intelligence, and still use quantities of traditional technologies and machinery and equipment in the production of their products, and their completion of the entire production process must rely on manual operations. And intelligent manufacturing can realize the final integration of man and machine through the network connection between intelligent machines, and its production organization mainly uses a new generation of information technology, using cloud computing, big data, and software analysis technology means to realize the intelligent operation and intelligent diagnosis of the production process [13]. Intelligent manufacturing can make production safer, efficiently, and environmentally friendly, which is an important driving force in the upgrading process of China's manufacturing industry and has a very important role in responding to emergencies and public safety events [14]. Simultaneously, intelligent manufacturing in the pharmaceutical sector has garnered significant attention due to its close association with epidemics.

Pharmaceutical manufacturing involves the national economy and people's livelihood, and is related to the strategic deployment and development stability of the country. As an indispensable part of the national economy, the development of the pharmaceutical industry is closely related to China's medical care level and the life and health of the nation, and in recent years, China's pharmaceutical industry has maintained a relatively stable development trend [15]. The large-scale prevalence of COVID-19 has prompted the state and all sectors of the community to increase the attention and concern to the healthcare industry [11,16]. As the aging trend of China's population significantly increases, the government will continue to strengthen policy support for the development of healthcare, along with the rapid development of scientific and innovative technologies in the field of pharmaceuticals, as well as the people's increasing awareness of healthcare, China's market demand for pharmaceutical products will continue to maintain a growing trend, and the intelligent manufacturing transformation of pharmaceutical manufacturing enterprises is imminent. Then, how to realize intelligent manufacturing transformation and upgrading of pharmaceutical manufacturing enterprises? Pharmaceutical manufacturing enterprises transformation and development process presents what evolutionary law?

In fact, the intelligent manufacturing transformation of manufacturing enterprises is a systematic project, the nature of which is a process of continuous development and improvement, and due to its multidimensional characteristics, it needs to be continuously advanced and adjusted during the transformation process to adapt to the needs of different stages of intelligent manufacturing transformation [17]. The intelligent manufacturing transformation of traditional manufacturing enterprises has gone through a process of development and change from simple to complex, in which need to realize path innovation and synergistic development of internal and external environments [18]. Organizing the literature, it can be found that scholars try to reveal the factors affecting enterprise transformation and the logical relationship of intelligent manufacturing transformation [19], and to explore the intrinsic connection between information technology and intelligent manufacturing transformation and upgrading [20,21], but few scholars have conducted systematic and integrative research on the relationship between the formation of affordances and the results of intelligent manufacturing transformation, much less on the basis of which the general law has been revealed. Existing studies have also yet to integrate the internal and external influences of smart manufacturing in manufacturing enterprises, ignoring the role mechanism of path creation evolution in complex systems [22], and failing to accurately reflect the actual results of enterprises' use of technological tools to realize smart manufacturing. Therefore, the study of the evolutionary law of enterprise intelligent manufacturing transformation as well as the adoption of feasible decision analysis methods to solve the path selection problem is an important issue worthy of attention in the academic and business communities.

In view of this, this study selects China Resources(CR) Jiangzhong pharmaceutical manufacturing enterprises as the research object, and on the basis of drawing on and summarizing the research literature on the intelligent manufacturing transformation of previous enterprises, it explores the evolution mechanism of the intelligent manufacturing transformation of pharmaceutical manufacturing enterprises, and how the development process of the intelligent manufacturing transformation of pharmaceutical manufacturing enterprises presents the law of evolution and other issues. First, based on system dynamics, clarify the boundaries of the manufacturing intelligent manufacturing system, distinguish the subsystems, and establish the basic model diagram of the system; Second, establish the causality loop diagram and construct the system stock flow diagram; Third, use the built-in DYNAMO language of Vensim Ple to construct the system dynamics model of the schematic results of the intelligent manufacturing platform and simulate the simulation; Finally, based on the analysis of the results of the simulation, it provides certain references and lessons for traditional pharmaceutical manufacturing enterprises to successfully realize intelligent manufacturing transformation.

2. System model design

Affordance has its roots in ecological psychology, where scholars in the field define affordance as the possibility of a behavioral agent to accomplish a certain action with the help of elements of the surrounding environment or objective things [23]. Over time, the field of ecopsychology has gradually begun to study affordance from an ontological perspective as a symbiotic evolutionary relationship between living organisms and their external environment, which involves a multitude of probable behaviors [24,25]. As the research on the affordance perspective became richer and more mature, affordance was extended to the fields of organizational management, organizational behavior, and organizational change. In subsequent studies, scholars proposed the concept of technology affordances, which refers to the ability of actors to achieve goals and use information technology, and this conceptualization further explains why the use of the same information technology also produces different performance outcomes [26]. Typically, in the process of enterprise transformation and upgrading, affordances are used to describe the interactions between the enterprise organization and the environment [27], and in the process of intelligent manufacturing transformation in pharmaceutical manufacturing enterprises, the enterprises use information technology to adopt behaviors that contribute to the achievement of the desired goals based on the perceived technological affordances affected by the environment [28,29] that thereby realizing intelligent manufacturing transformation. Therefore, this paper defines the environmental factors affecting the formation of affordances as the affordance environment.

Developments in the field of complex adaptive systems have provided a new perspective and methodology for exploring the internal evolution laws of complex dynamical systems, as well as targeted solutions for the dynamic evolution of intelligent manufacturing transformation in pharmaceutical manufacturing enterprises [30]. Based on this, this paper explores the dynamic evolution process of pharmaceutical manufacturing enterprises' intelligent manufacturing transformation using digital technology by taking the formation and realization of technology affordances as a foothold in the case study of CR Jiangzhong, and starting from the dynamical system that drives pharmaceutical manufacturing enterprises to realize intelligent manufacturing. Then, through the method of system dynamics, with the help of Vensim Ple computer modeling simulation software, we analyze the adaptive evolution mechanism of pharmaceutical manufacturing enterprises using the affordance environment to realize intelligent manufacturing transformation in the dynamic environment, and explore the synergistic evolution law of the ecosystem development of the affordance environment.

2.1. Source power of enterprise resources heterogeneity and organizational management

A key element for enterprises to achieve competitive advantage is the organizational capability to effectively integrate and deploy resources into highly competitive products and services [31,32]. The potential value of resources can only be realized if organizational capabilities are fully utilized. Organizational capacity involves the transformation of production factors and resources of an enterprise, which refers to the effective application of resources to the production process and the formation of a set of socialized routines to guide individuals in accomplishing their tasks [33]. It is not only a behavioral pattern, but also an abstract cognitive law that can reveal the mechanism in the "black box" of resource transformation, which determines the productivity of resources and the performance of the enterprise.

Varadarajan (2020) [34] states that resource heterogeneity is the difference between the bundles of resources, bundles of capabilities, and bundles of core competencies possessed by enterprises, which is the basis of their competitive advantage. Resource base theory suggests that the initial difference lies in the different nature of resources owned by enterprises and resource heterogeneity may give enterprises different competitive advantages [35]. However, heterogeneous innovation resources alone cannot bring lasting competitive advantage to enterprises, and must be reintegrated and create a price of use through the enterprise's existing resources to help enterprises enhance their competitive advantage. The possession of heterogeneous resources by enterprises is a key factor for them to have a competitive advantage and to sustain in the industry in which they operate.

2.2. Support power of technological innovation and pharmaceutical policy

Technological innovation has become the core of intelligent manufacturing by using specialized services as the main mode of operation and using big data analysis and processing capabilities [4], to provide customized solutions to meet the needs of manufacturing enterprises to upgrade their products and services. Technological evolution nourishes innovation, while the support of high technology facilitates integrated interconnections at the device and control layers [36]. Thus, technological innovation plays a key role in accelerating the adoption of high technology.

Government, as a catalyst for growth and unlimited enabler, has a strong advocacy and incentive role for business enterprises to transform social enterprises [37,38]. Government support can increase the supply of impact investments, or those interested in social and financial returns; government also increases the demand for impact capital or strategically directed channel capital, all aspects that are attractive to business enterprises transforming social enterprises [39]. The transformation of business enterprises in pursuit of maximizing social impact can gain recognition and support from the public and government [40], while at the same time, the label of social enterprise can help enterprises to obtain policy subsidies and preferential access to government-purchased services. In addition, in the process of business environment enhancement, government support, as a positive shaping factor of the entrepreneurial environment, facilitates business enterprises to innovate their own organizational concepts and forms, and transform to a more inclusive value realization model [41].

2.3. Driving power of market environment demand and industry competition

With the advancement of technology and the intensification of competition, enterprises are faced with both opportunities and challenges, changes in potential consumer demand, changes in industry structure, and the response strategies of suppliers and competitors, which have posed great challenges to the traditional manufacturing industry in a complex business ecosystem, forcing enterprises to start intelligent manufacturing transformation and upgrading [4,42].

The normal operation and growth of a business is based on market demand [43]. Due to the variability of the market environment and the changing needs of customers, enterprises must take sound investment decisions and develop new products and services in a timely manner to meet the changing needs to maintain their dominant position in today's competitive market [44,45]. In addition to this, enterprises need to continuously optimize and upgrade, and innovatively develop their products and service models to better meet the needs of customers, bring greater value to the enterprise, and gain a long-term advantage in the competition [46,47]. Enterprises analyze and study the collected data, develop a reasonable business model by understanding the needs of potential customers in a timely manner, and invest in reasonable digital information technology for this purpose, to meet the needs of customers and provide them with high-quality products and services, which helps to promote the transformation of enterprises to realize service-oriented intelligent manufacturing.

This study is based on two basic assumptions: first, enterprises should fully consider information technology at the time of their establishment, not only limited to those who have invested heavily in informatization; second, this model focuses on the meso-organizational level of realizing the intelligent manufacturing transformation and incorporates the influence of micro-individual factors to reflect the actual situation more accurately. This study constructs a theoretical architecture as shown in Fig. 1, with a view to exploring the key mechanisms and core concepts of this process in depth, while improving the accuracy of the system model.

3. Methods

3.1. System dynamics modeling

System dynamics has been proved to be an effective method for dealing with large-scale, complex and dynamic systems, and is particularly applicable to the problems of long-term development cycles and complex feedback systems [48]. System dynamics modelling has been applied in many fields and has proved to be instructive in solving dynamic and complex system problems. In fields such as education, economics, policy, environment, medicine and health, researchers are increasingly using system dynamics to study various systems and problems [49,50]. System dynamics modelling not only describes the current situation, identifies influencing factors, and predicts future trends, but also observes changes under different policy scenarios [48,51,52]. System dynamics modelling has distinct advantages over other approaches, including an understanding of the various levels of influence on a particular population or issue, the study of circular feedback processes, and the ability to explain and understand dynamic interactions. In contrast, system dynamics modelling overcomes some of the shortcomings of other approaches, such as isolated, statical and one-sided analyses, and is therefore a powerful tool when exploring complex management issues.

In terms of system dynamics modelling, this paper will construct a system dynamics model in combination with the specifics of the intelligent manufacturing transformation of pharmaceutical manufacturing enterprises to study its evolution mechanism. By observing the perspectives of causality and structure-determined behaviour, we will build the model from the internal microstructure of pharmaceutical manufacturing enterprises, analyze the intrinsic relationship between system structure and function as well as dynamic behaviours, and then use computer simulation to explore various policy scenarios in the process of smart manufacturing transformation of pharmaceutical manufacturing enterprises and observe the long-term results of the implementation of different policies.

3.2. Causal loop diagram

The realization of an enterprise's intelligent manufacturing strategy through the adoption of information technology is a mechanism by which the enterprise uses information technology to achieve synergistic evolution with the external environment. Therefore, to achieving specific business goals, organizations must use information technology to support their realization process and make use

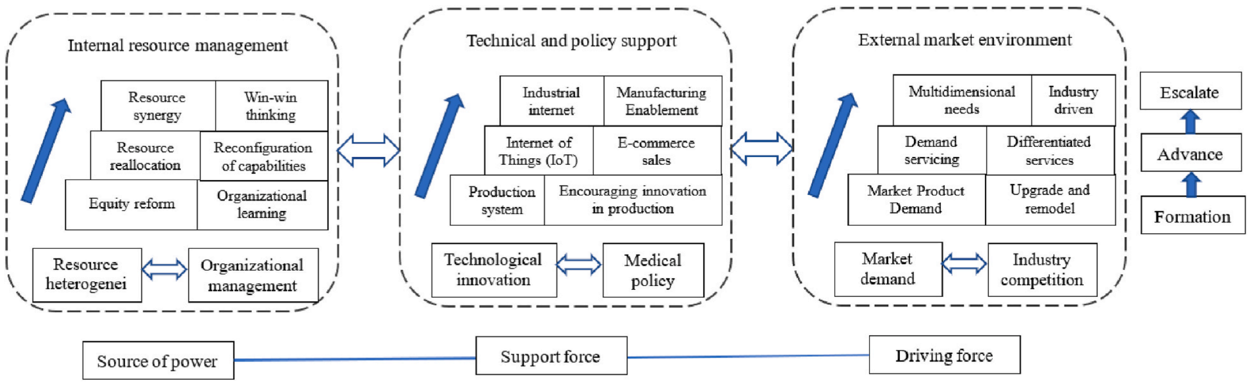

Fig. 1. Basic model diagram of the system.

of existing resource capabilities to optimize and enhance their products, operations, business processes, etc. These specific implementation actions will help promote enterprises to achieve economic benefits based on scientific and effective smart manufacturing strategies: on the one hand, enterprises can optimize existing products and services to better meet customer needs and improve utility; on the other hand, enterprises can take the market as the guide to re-construct the business model, access to new resources, and the integration and deployment of these resources to expand into new segments of the market and provide specific products and services to obtain stronger market competitiveness. Based on the conceptual model of intelligent manufacturing transformation, and combined with the main influencing and driving factors, the causal loop diagram can be established with the Vensim software, which can clearly show the interactions and interrelationships between the key factors [48,51], in which "+" stands for having a facilitating effect, "-" stands for having an inhibitory effect, "R" denotes a positive feedback loop, and "B" denotes a negative feedback loop, and the main structure of the major feedback loops is shown in Fig. 2 below.

(1) Feedback loops of path creation for organizational resource capability

In the transformation process of manufacturing enterprises, latecomer enterprises as followers are constrained by their innovation resources, and face more difficulties and challenges due to the constraints of leading enterprises in technology and market. Therefore, these enterprises require unique technological advantages to realize catch-up innovation through "path creation" [53] to break through the dilemma of path dependence. Arthur (1994) [54]and David (1985) [55] have examined the phenomenon of path dependence in the process of technological innovation and called it path dependence. How to break through path dependence and realize path creation has been a concern of scholars, some scholars believe that external factors can bring changes, while others believe that internal factors are the key to path creation.

Schumpeter's idea of "creative destruction" emphasizes the decisive role of entrepreneurial willpower in the creation of new development paths [56]. In addition, Garud and Karnoe (2003) [57] explicitly proposed the concept of "path creation", arguing that the breakthrough of path dependence is often a conscious deviation. Path creation is the process by which enterprises break through the limitations and boundaries of existing systems, technologies, etc., with the aim of enhancing the adaptive capacity of the organization to achieve sustainable development [58]. Pathways or practices that have been accumulated over the history of an organization should not be limited to "limitations" but rather seen as proven ways of doing things, and innovation pathways are largely based on these pathways, thus creating a symbiotic evolutionary relationship [59]. Path creation can be divided into two dimensions: technological innovation capability and institutional optimization capability [60]. Technological innovation capability takes traditional industries

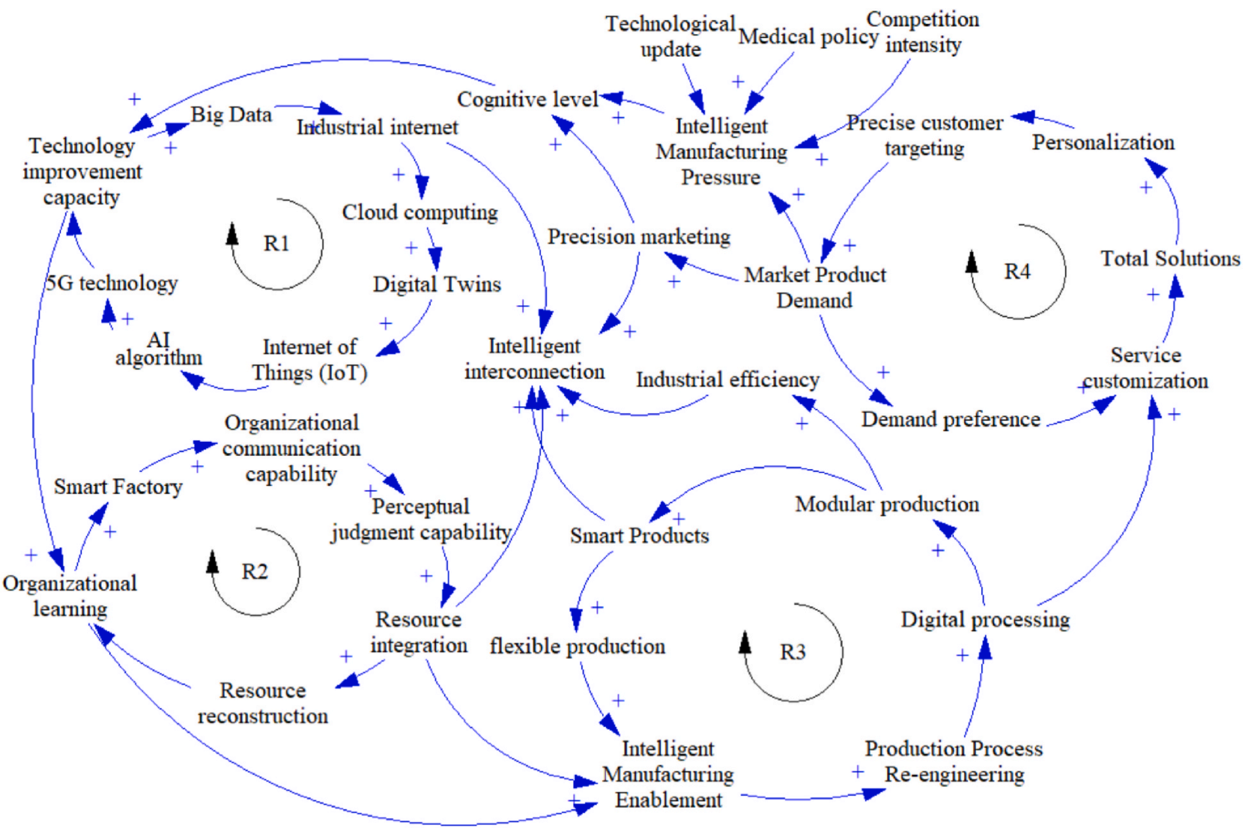

Fig. 2. Causal loop diagram.

as the basis and enhances the adaptive capacity of the organization by incorporating intelligent technology, so as to realize the synergistic development of intelligence and traditional industries [61]; whereas institutional optimization capability stems from the scientific and prospective nature of the scheme in the process of accelerating the deep integration of intelligence and the real economy of the organizational managers on the basis of their organizational learning and perception capabilities, as well as the artificial intelligence itself technical characteristics of the driving mechanism of institutional optimization [62]. Institutional optimization capabilities can be attributed to the causal loop as R1.

R1. Organizational Learning → Organizational Communication Capability → Perception and Judgment Capability → Resource Integration → Resource Reconstruction →Smart Factory

(2) Feedback loop of digital technology innovation capability

With the continuous popularization of new-generation science and technology such as artificial intelligence, the Internet of Things, digital twins, and other new technologies, their computing power and algorithmic support provide a reliable technological foundation for the industrial Internet platform. It has enabled the traditional manufacturing industry to achieve data-based intelligent manufacturing and revolutionises the operation and management model of the IT era [63,64]. The era of digital economy reconfigured by "data + computing power + algorithm" provides a new development opportunity for the traditional manufacturing industry.

Industrial big data plays an increasingly important role [65], which not only collects data from PC ERP, finance, HR, and other process systems, but also connects these data, overcomes the problem of internal segmentation of the system, and realizes the effective flow and utilization of data. The transformation of industry from data to big data has realized the integration of informatization, industrialization and automation data, forming a seamless and complete data system, and integrating data from upstream, downstream and cross-border of the industry chain, which provides support for data-driven comprehensive upgrading.

Computing technologies such as cloud computing and edge computing greatly improve the efficiency and accuracy of processing large amounts of data, while algorithmic technologies such as artificial intelligence and mechanism modeling help smart manufacturing to discover patterns and provide the support needed for digital operational decision-making [66,67]. In addition, the network integration of 5G and TSN (Time Sensitive Network) gives full play to its advantages of fast transmission, wide coverage, low latency, etc., and realizes the mutual integration of the elements of "data + computing power + algorithms" to realize collaborative operations, thus exerting great value. The feedback loop of intelligent manufacturing transformation digital technology innovation capability is R2 in Fig. 2.

R2. Big Data → Industrial Internet → Cloud Computing → Digital Twins → Internet of Things (IoT) →AI Algorithms → 5G Technology → Technology Improvement Capability

(3) Feedback loop of smart product production capacity

Since the Industrial Revolution, enterprises have attempted to replace labor with machinery to increase productivity. With the spread of automation, further efficiency gains must rely on continuous improvements in mechanical equipment or management tools [68]. In addition, the convergence of artificial intelligence and manufacturing technology marks the opening of a new generation of industrial technological revolution and offers a new technological approach and economic paradigm to the manufacturing industry, presenting a new development opportunity for latecomers [64,69]. Furthermore, with the emergence of emerging industries such as cloud computing and smart factory solutions, enterprises are carrying out scenario-dependent personalized innovations in response to the technological needs of transforming production equipment and optimizing management tasks, represented by production capacity circuits for smart products, which achieve a continuous improvement in productivity, and are represented as R3 in Fig. 2.

R3. Intelligent Manufacturing Enablement → Production Process Reengineering → Digital Processing → Modularized Production →Smart Products → Flexible Production

(4) Feedback loop for customizing network product market demand

The rapid growth of information technology and mobile Internet enables consumers to participate in the whole process of production and value creation of enterprises through extensive and real-time participation, which leads to a fundamental change in the relationship between enterprises and consumers [70], and the dominant power of the enterprise value chain is shifted from the enterprises to the consumers. This requires manufacturing enterprises to be customer-centric, adopt new technologies such as network marketing and mobile terminals to achieve precise interaction with users and promote customized services to meet the diverse and individualized needs of users [71,72]. Meanwhile, through big data analysis of customers, enterprises can forecast the market and distill the common needs of user groups, which enables both personalized manufacturing and mass production while saving a lot of costs. The feedback loop for customizing network product market demand is R4 in Fig. 2.

R4. Market Product Demand → Demand Preference → Service Customization → Overall Solution →Personalized Customization → Customer Precision Positioning

The main circuits formed based on the above analysis are as follows:

Cognitive Degree → Technological Capability Improvement → Organizational Learning →Intelligent Manufacturing Enablement →

Production Process Reengineering → Digital Processing → Modular Production →Smart Products → Intelligent Interconnections → Industrial Efficiency → Market Product Demand → Demand Preferences → Service Customization → Overall Solution → Personalized Customization → Customer Precision Positioning → Market Product Demand → Intelligent Manufacturing Pressure → Cognitive Degree.

3.3. System flow diagram

To provide an accurate and rational analysis of the model, the various variables in the model must be quantified. The preceding causal feedback loops can express qualitative relationships and provide the basis for constructing a system stock-flow diagram. The stock-flow diagram can be used to describe the causal links between the elements of the system, accurately indicate the characteristics of the variables and feedback and control mechanisms [51,73], through the analysis of the causality diagram based on the causality diagram, further system-flow diagram models can be constructed for the technological innovation-driven intelligent manufacturing system of manufacturing enterprises, see Fig. 3 below. The stock variables are state variables and are represented as rectangles in the figure; inputs and outputs between stocks are connected by flow variables, which represent rate variables and are represented by double-line arrows; interrelationships between various variables are connected by single-line arrows.

(1) Types of variables

According to Fig. 3, a total of 4 state variables, 8 rate variables, 20 auxiliary variables and 4 constants are composed of the modeling equations, and the variable explanations can be found in Table 1 to express the modeling equations more clearly.

(2) Variables equations

From the principle of system dynamics, it is known that in contrast to precise numerical settings, system dynamics modelling focuses on the structure of the system, and when the operating parameters do not exceed a certain range, the modelled results can be obtained in line with reality [73,74]. The core variables of this system consist of 4 state variables and 8 rate variables, to better simulate the intelligent manufacturing transformation path, this paper refers to and draws on the research results and case data of Zhang et al. (2021) [74], Luo et al. (2022) [52], Qiao et al. (2024) [50] and establishes the corresponding equations for the core variables, and the state variables are represented by integral equations, t0 stands for the starting time, t represents the time elapsed by the system, and the equations are respectively:

$$L1(t) = \int_0^t [R1 - R2]\mathrm{d}s + L1(t0)$$

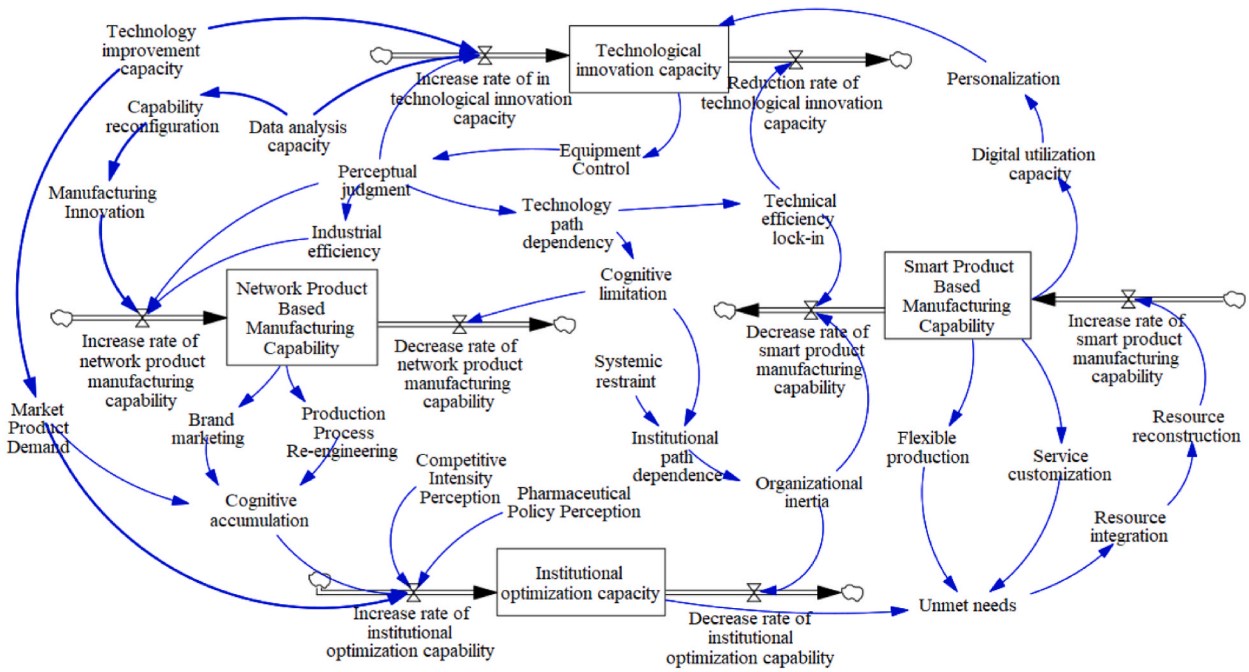

Fig. 3. Stock flow diagram.

Table 1
Explanation of system variables.

Variable Type	Number	Variable Name
State variable	4	Technological Innovation Capability L1, Institutional Optimization Capability L2, Network Product Based Manufacturing Capability L3, Smart Product Based Manufacturing Capability L4
Rate variable	8	Increase rate of technological innovation capability R1, Decrease rate of technological innovation capability R2, Increase rate of institutional optimization capability R3, Decrease rate of institutional optimization capability R4, Increase rate of network product manufacturing capability R5, Decrease rate of network product manufacturing capability R6, Increase rate of smart product manufacturing capability R7, Decrease rate of smart product manufacturing capability R8
Auxiliary variable	20	Perception and Judgment Capability A1, Ability Reconstruction A2, Manufacturing Innovation A3, Industrial Efficiency A4, Equipment Control A5, Technology Path Dependence A6, Technology Efficiency Lock-in A7, Cognitive Limitations A8, Institutional Constraints A9, Institutional Path Dependence A10, Organizational Inertia A11, Market Product Demand A12, Brand Marketing A13, Production Process Re-engineering A14, Cognitive Accumulation A15, Demand Failure to be Satisfied A16, Flexible Manufacturing A17, Service Customization A18, Resource Integration A19, Resource Reconfiguration A20, Digital Utilization Capability A21, Personalized Customization A22
Constant	4	Technology Improvement Capability C1, Data Analysis Capability C2, Pharmaceutical Policy Perception C3, Competitive Intensity Perception C4

$$L2(t) = \int_0^t [R3 - R4]\mathrm{d}s + L2(t0)$$

$$L3(t) = \int_0^t [R5 - R6]\mathrm{d}s + L3(t0)$$

$$L4(t) = \int_0^t [R7 - R8]\mathrm{d}s + L4(t0)$$

To reveal the characteristics of the rate variables, it is necessary to combine them with the relevant factors affecting the state variables and to establish the equations used to characterize the main auxiliary variables so that the provide an in-depth analysis of the relationships between the variables:

$$R1 = f1(A1, A2, A3)$$

$$R2 = DELAY1\, f2(A9)$$

$$R3 = SMOOTH\, f3(A14, A17, C1, C2)$$

$$R4 = f4(A13)$$

Table 2
Key variables and equations.

Variable name	Variational equation
Technological innovation capacity	INTEG (rate of increase in technological innovation capacity - rate of decrease in technological innovation capacity, 35)
Institutional optimization capacity	INTEG (Increase rate of institutional optimization capability - Decrease rate of institutional optimization capability, 45)
Web-based product manufacturing capabilities	INTEG (Increase rate of network product manufacturing capability - Decrease rate of network product manufacturing capability, 10)
Manufacturing capabilities based on smart products	INTEG (Increase rate of smart product manufacturing capability - Decrease rate of smart product manufacturing capability, 30)
Increase rate of technological innovation capacity	Technology improvement capability * 0.3 + Data analysis capability * 0.1 + Perception and judgment capability * 0.3
Decrease rate of technological innovation capacity	Technical efficiency lock * 0.8
Increase rate of institutional optimization capability	Market product demand * 0.3 + Cognitive accumulation * 0.2 + Perceived competitive intensity * 0.4 + Perceived pharmaceutical policy * 0.2
Decrease rate of institutional optimization capability	Organizational Inertia * 0.2
Increase rate of network product manufacturing capability	Manufacturing innovation * 0.2 + Perception and judgment capability * 0.3 + Industrial efficiency * 0.4
Decrease rate of network product manufacturing capability	Cognitive limitations * 1.4
Increase rate of smart product manufacturing capability	Resource reconfiguration * 0.7 + Digital utilization capability * 0.5
Decrease rate of smart product manufacturing capability	Technical efficiency lock * 0.6+ Organizational inertia * 0.4

$$R5 = f5(A3, A5, A6)$$

$$R6 = f6(A10)$$

$$R7 = f7(A9, A13)$$

$$R8 = DELAY3\, f8(A22)$$

The model is simulated from month 0 to month 100 in steps of one unit per month:
INITIAL TIME = 0.
Units: months.
FINITAL TIME = 100.
Units: months.
TIME STEP = 1.
Units: month.

In addition, the data were partly obtained from China Statistical Yearbook and China Science and Technology Statistical Yearbook, and the simulation process mainly used the relevant data of the pharmaceutical manufacturing industry, and the time span of the data was from 2013 to 2023. Combined with the system dynamics variables to design equations and determine the values of parameters, the main variables are set up variable equations as shown in Table 2.

4. System dynamics model simulation and result analysis

4.1. Simulation analysis

Information technology use and institutional logic are used as tools to support companies in their smart manufacturing strategy, which pharmaceutical manufacturing companies want to use to upgrade and optimize their existing manufacturing and business processes, and to provide new products and smarter services. Based on the stock flow diagram, the simulation results are analyzed below.

(1) Technological innovation capability

As shown in Fig. 4 below, pharmaceutical manufacturing enterprises improve their research on product innovation and intelligent scientific production by using intelligent advanced technologies such as big data and industrial Internet, create smart products and intelligent customer service capabilities, improve industrial efficiencies by improving equipment control capabilities, and enhance their technological innovation capabilities. Enterprises are facing digital change, and the development of advanced technologies such as cloud computing and the Internet of Things has provided them with an extremely effective digital infrastructure, through which they can effectively improve equipment production efficiency and operational efficiency and realize the basic operation mode of the enterprise.

Technological innovation includes the development of new technologies as well as the application of innovation to existing technologies. Industrial Internet, modeling and simulation technology and intelligent technology are all key technologies for the development of intelligent manufacturing, which is the core of intelligent manufacturing and the source of technological evolution. At the same time, to realize the integration and interconnection at the equipment level and control level, the support of high technology is

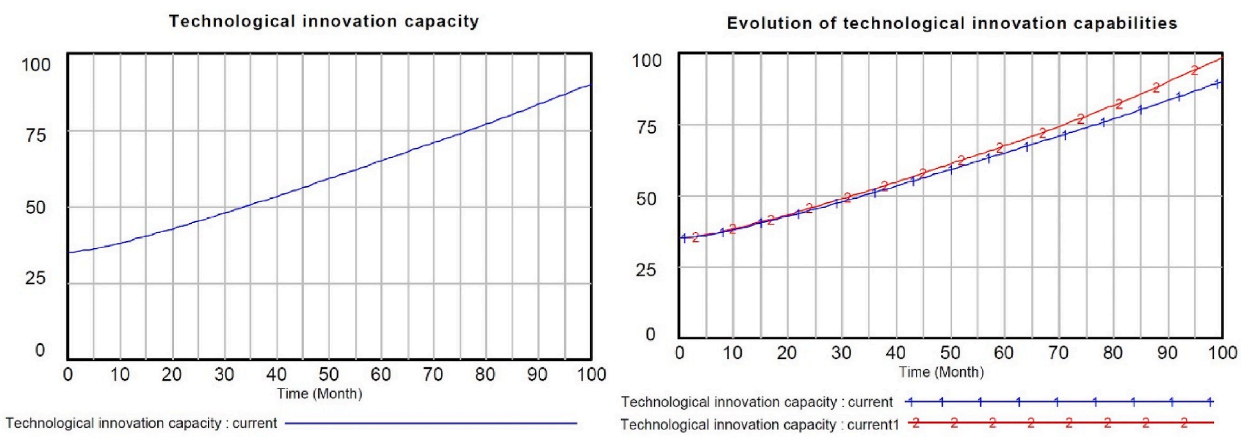

Fig. 4. Technological innovation capacity L1.

also necessary, and technological innovation can promote the application of high technology with higher efficiency.

(2) Network product based manufacturing capability

As can be seen from Fig. 5, the continuous improvement of technological innovation capacity provides strong technical support for the manufacturing capacity of network products, thus providing a reliable guarantee for enterprises to improve productivity. With the development of Internet technology, technological innovation capacity based on the Internet of Things and cloud computing, enterprises develop their own Internet platform system to solve the communication and demand problems between end users and enterprise R&D and production. Manufacturing enterprises through the production process reengineering for deep digital processing, for the realization of the customer's personalized customization provides a solid foundation. Technological innovation and market demand to stimulate the enterprise for the customer's overall service solutions, but also to enhance the network product manufacturing capacity.

(3) Institutional optimization capability

Through the analysis above, the technological innovation ability and the manufacturing ability of network products are the basis for forming the institutional optimization capability of pharmaceutical manufacturing enterprises, which can be seen in Fig. 6 that the institutional optimization capability is being gradually improved. This shows that through big data and technological innovation, enterprises can obtain external data about industry competition, market environment and other external data, so that they can have a sharper insight into the changes in industrial structure, market demand, and changes in the supplier and competitive environment, and enhance their sensitivity and adaptability to the external environment.

In the process of enterprise intelligent manufacturing transformation, during different periods of transformation, there are government policy institutional logic, enterprise managers institutional logic, market demand institutional logic and other institutional logics coexisting or co-inhabiting, and interacting with each other to promote the evolutionary development of enterprise transformation. Utilizing the interaction of various institutional logics to accelerate the deep integration of artificial intelligence and the real economy, this process has programmatic scientific and forward-looking. With the integration of technology, traditional industries need to reintegrate resources and optimize management processes based on technological innovation to enhance industrial efficiency and competitiveness.

(4) Smart product based manufacturing capability

As can be seen from Fig. 7, institutional optimization capability is the foundation of the manufacturing capability of smart products, and the improvement of institutional optimization capability constantly promotes the improvement of the manufacturing capability of smart products. When manufacturing enterprises perceive the development trend of new technology and new demand, and have strong technological innovation capability and institutional optimization capability, they can formulate a perfect strategic policy and implement effective reform measures according to the analysis of market demand and competitive environment to enhance their competitiveness. At the equipment level, the manufacturing system has realized intelligent development through continuous innovation of key technologies as well as research and development of core components, and breakthroughs in equipment control and management technologies. At the control level, large quantities of intelligent equipment and intelligent components are applied to the automated production line, constituting an intelligent production line. At the management level, by utilizing advanced technologies such as big data analysis and cloud computing, a system based on decision-making and management is built to form an smart factory consisting of a physical factory, a virtual factory and an intelligent decision-making and management system.

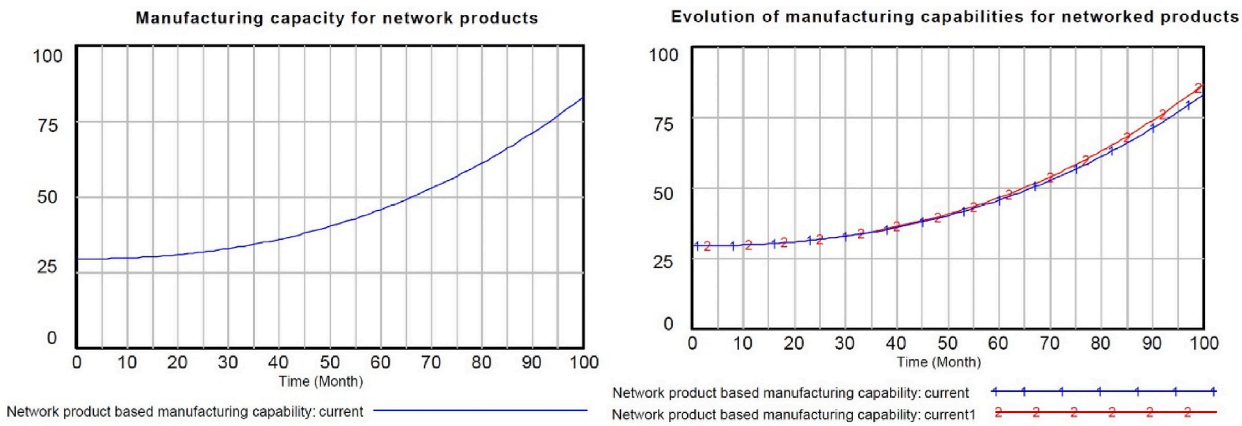

Fig. 5. Manufacturing capacity for network products L3.

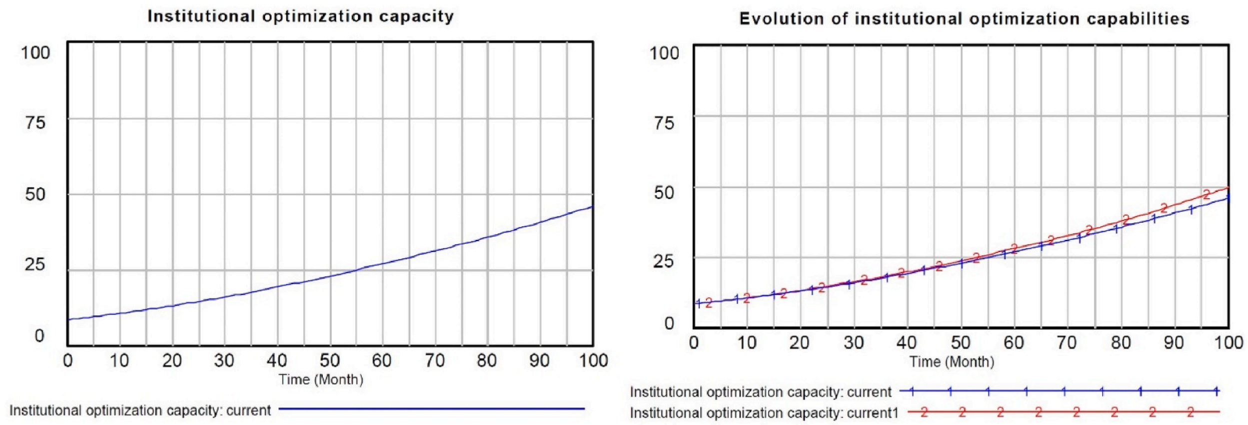

Fig. 6. Institutional optimization capability L2.

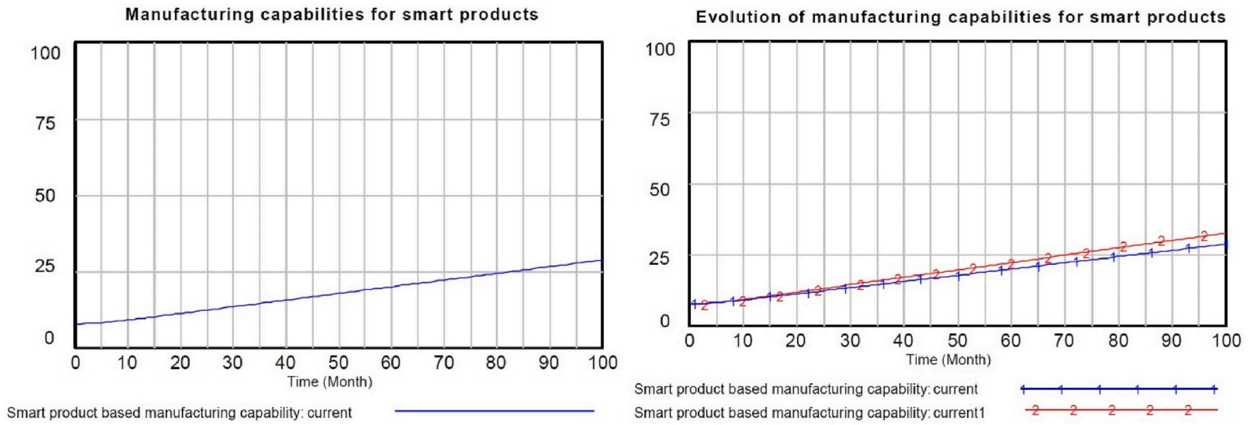

Fig. 7. Manufacturing capacity for smart products L4.

4.2. *Integrated system model analysis*

According to the comprehensive simulation Fig. 8, technological innovation capability and network product-based manufacturing capability are the foundation of intelligent manufacturing transformation of pharmaceutical manufacturing enterprises. The starting point of L1 and L2 is significantly higher than that of L3 and L4, so it is not enough for enterprises to rely only on their existing knowledge and cognitive experience. Only by enhancing product manufacturing capability through technological innovation can

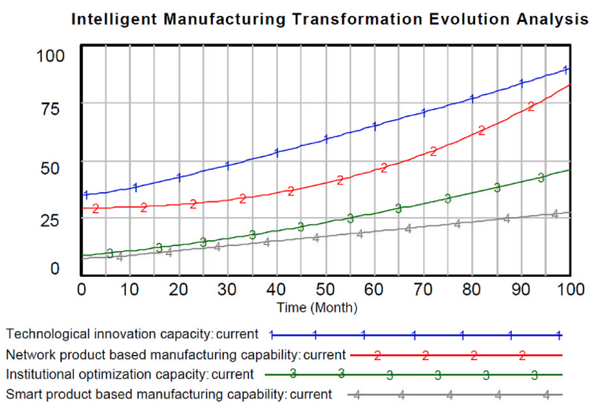

Fig. 8. Evolutionary mechanism of intelligent manufacturing transformation in pharmaceutical manufacturing enterprises.

enterprises realize their own evolution and be able to collaborate with changes to meet customers' demand and provide better products and services. This process requires time to accumulate, gradually deepen, to realize the intelligent manufacturing transformation of pharmaceutical manufacturing enterprises.

The first path of intelligent manufacturing is the primary manufacturing stage, in which enterprises standardize their core business and digitize their processes through digital information technology to provide products of excellent quality and diversified services, and to enhance users' product usage and service quality. The continuous improvement of technological innovation provides strong support for the manufacture of network products, helping manufacturing enterprises to improve production efficiency and achieve comprehensive digital and intelligent manufacturing. With the development of Internet technology, technological innovation capability based on the Internet of Things and cloud computing, enterprises develop their own Internet platform system to solve the communication and demand problems between end-users and enterprise R&D and production. Manufacturing enterprises through the production process reengineering, deep digital processing, through the realization of personalized customization for customers to provide a solid foundation. Technological innovation and market demand to stimulate the enterprise for the customer's overall service solutions, but also to enhance the Manufacturing capacity for network products.

At this stage, enterprises have acquired rich data resources in their reserves, which can be organized and analyzed not only to provide support for their production and operation, but also to provide methods and rules for their development of product and service integration. In terms of production, the continuous improvement of production capacity and level, the realization of product diversification, a variety of design and production, which not only improves the production efficiency of the enterprise, but also promotes the development of technology related to the integration of products and services. In terms of management, we have improved the resource planning management system and applied it to all internal departments, realized network management of enterprise operations through technical means, and realized detailed enterprise management; meanwhile, the improvement of management efficiency has strongly promoted the development of technologies related to the integration of products and services. In terms of service, to meet the needs of customers and improve customer satisfaction, the enterprise focuses on the development of solutions for the integration of products and technologies, which not only improves the flexibility and accuracy of the enterprise, but also greatly improves the efficiency of the enterprise's operation through the categorization and organization of data resources, diversified production, and networked management.

The second intelligent manufacturing path is the high-level manufacturing stage, which mainly adopts an intelligent and efficient way to transmit a large amount of information to the optimization decision-making system to realize the collection, storage, analysis, auto identification and rapid cognition of big data. Then with the support of the computing platform, a large amount of heterogeneous information is automatically mined and extracted from the product's entire life cycle, and through reasoning and prediction to form decision-making instructions to optimize the manufacturing process, through which the execution system can control the state of the manufacturing process to achieve stable and safe operation and dynamic adjustment of the system, so as to achieve the customer's goals and optimize the business process.

At this stage, the application of new-generation information technology enables sensors and system platforms to work together to automate the operation and analysis of production systems. Such systems can predict potential risks in advance and enable real-time data collection and timely analysis. In terms of intelligent production, with the help of new-generation information technologies such as the Internet of Things and cloud computing, it is possible to remotely monitor and manage the operation of products, which greatly promotes the integration and development of information technology and manufacturing technology, effectively shortens the checking time of technical failures, and reduces the cost of production and operation. In terms of intelligent management, by utilizing the intelligent management system platform independently developed by artificial intelligence technology, it gives full play to the role of big data prediction and other technologies, facilitates the comprehensive management of the enterprise, and puts forward reasonable decision-making suggestions on many specific matters, such as the operation and maintenance of equipment. In terms of service marketing, to accelerate adaptation to changes in market demand, including real-time data collection and analysis, remote operation and maintenance, and intelligent and rational decision-making, it lays the foundation for the provision of full life cycle solutions based on intelligent products and services.

The significance implied behind these two paths above is that intelligent manufacturing transformation of pharmaceutical manufacturing enterprises should go through a gradual and progressive process. The network product manufacturing as the core is the primary stage of intelligent manufacturing transformation, applicable to those enterprises that lack knowledge of intelligent manufacturing but are driven by the external environment to implement intelligent manufacturing transformation. The one centered on the manufacturing of smart products is the advanced stage of intelligent manufacturing transformation, in which enterprises must accumulate basic practical experience in intelligent manufacturing and possess good competitiveness to cope with changes in the external environment, while the intelligent manufacturing in the primary stage is the cornerstone for realizing the advanced stage.

5. Discussion and implications

5.1. Conclusion

Each industrial revolution promotes the transformation of organizational forms, and these changes bring new phenomena and issues for business transformation, thus contributing to the continuous development of organizational theory body of knowledge. Previous scholars have studied the relationship between digital information technology and intelligent manufacturing transformation from different perspectives [5, 64]. However, few scholars have summarized the co-evolutionary patterns of influencing factors, organizational changes, and intelligent manufacturing transformation from an evolutionary perspective. This paper draws on the idea of system dynamics to analyze the results and evolutionary laws of manufacturing enterprises realizing intelligent manufacturing transformation driven by technology affordances.

The results of the study can be summarized in the following points: first, the study found that pharmaceutical manufacturing enterprises have achieved network product-based manufacturing capability and smart product-based manufacturing capability through technological innovation capability and institutional optimization capability, respectively, using technology affordances to provide support. Intelligent manufacturing based on networked products is in the primary stage, providing a solid foundation for transformation and a key step in developing from primary to advanced intelligent manufacturing. Second, the technology affordances environment promotes pharmaceutical manufacturing enterprises to realize intelligent manufacturing transformation showing stage transformation law. The path creation of pharmaceutical manufacturing enterprises using technology affordances presents the law of technological innovation capability to institutional optimization capability, and the result of transformation presents the evolution law of low-level to high-level. Among them, technological innovation capability and institutional optimization capability are not substitutes, but coexist.

5.2. Theoretical contribution

First, the research paradigm of intelligent manufacturing transformation of enterprises is enriched and extended. Existing studies have elaborated on intelligent manufacturing transformation of manufacturing enterprises from different perspectives [6,7,75], but most of them focus on the impact of technological tools on the intelligent manufacturing performance of manufacturing enterprises [8,17], and have not yet explored the way manufacturing enterprises evolutionary law of adopting information technology tools to achieve dynamic development based on changes in the internal and external environments, and even fewer studies have focused on the real-world scenarios of manufacturing firms achieving intelligent manufacturing transformation outcomes through path creation. Therefore, based on the existing literature, this study adopts the system dynamics simulation research method to further explore the longitudinal path creation evolution law of the affordance environment and intelligent manufacturing of pharmaceutical manufacturing enterprises under the action of multiple influencing factors of the complex dynamic environment.

Second, it complements the application scenario of technology affordances theory. Previous research on enterprise intelligent manufacturing transformation is mostly based on dynamic capability theory [3], resource orchestration theory [22]and other perspectives to analyze enterprise transformation and upgrading. As a fundamental theoretical perspective of information technology-induced organizational change, technology affordances can better explain how information technology affects organizational change, but existing research has not yet explored the role of technology affordances in the process of intelligent manufacturing transformation of manufacturing enterprises, as well as the formation and realization process. This study finds that pharmaceutical manufacturing enterprises use technological affordances to provide support to realize the Manufacturing capacity for network products and smart products through technological innovation capability and institutional optimization capability, respectively, and the results of intelligent manufacturing transformation of pharmaceutical manufacturing enterprises show an evolutionary law from low to high level, which complements the study on the evolution of intelligent manufacturing transformation, and provides valuable clues for digging deeper into the interrelationships between the evolutionary stages.

5.3. Managerial implications

First, for manufacturing enterprises, intelligent manufacturing transformation is not only technological innovation, but also the key to management mode and organizational change. First, enterprises should deeply understand the role of technology affordances in promoting intelligent manufacturing. Integrate technological innovation and institutional optimization capability, build network product-based manufacturing capability for network products and smart products, and move from primary smart manufacturing to advanced development. Secondly, enterprises should flexibly respond to changes in the external environment, continue to innovate and make intelligent manufacturing a strategic goal for all employees, and promote cross-sector collaboration to realize comprehensive transformation.

Second, for the government, policies and regulations need to be formulated to support intelligent manufacturing transformation. Encourage enterprises to invest more in technological innovation, institutional optimization, network product and smart product manufacturing to promote intelligent manufacturing transformation. Provide resource support, such as technical training and research funding, to promote technology upgrading and application. The government and enterprises cooperate to establish long-term development plans to promote industrial upgrading and economic transformation.

5.4. Limitations and future research

Although this paper explains the process model of intelligent manufacturing transformation of pharmaceutical manufacturing enterprises and forms some valuable findings, there are still some shortcomings: firstly, this paper only explores the evolutionary path of intelligent manufacturing transformation of CR Jiangzhong pharmaceutical manufacturing enterprises, and there may be different evolutionary development paths in other traditional manufacturing industries, which are worth exploring in depth in the future; secondly, the intelligent manufacturing transformation of manufacturing enterprises has gradually become a transformational upgrade development, but has not yet attracted the attention of the academic community, especially in the traditional pharmaceutical manufacturing industry, more research methods can be used to test the framework of the theory in the future, such as case studies, questionnaires, experiments and other empirical studies.

Ethics statement

Not applicable.

Data availability statement

Data will be made available on request.

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CRediT authorship contribution statement

Wei Zhu: Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Ping Ouyang:** Methodology, Data curation, Conceptualization. **Mengnan Kong:** Software, Formal analysis.

Declaration of competing interest

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

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