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ORIGINAL PAPER

Exploring robustness management for dynamic technology fusion

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Abstract The concepts of technology fusion describe the phenomenon of technology overlap. Despite its importance, the evolutionary trajectories of technology fusion are not explored well. The main contributions of this article have two aspects: One is the mathematical modeling of a two-dimensional technology fusion system with technical efficiency and convergence parameters that can determine the evolution trajectories of technology fusion; the other is to reveal the dynamics of the evolution process through robust analysis and improving the stability of technology fusion under external disturbances. A novel technology fusion analysis method is proposed for technology fusion by applying dynamic development scenarios of manufacturing technology and information technology to be robust under external disturbances. In this article, firstly, we introduce technical efficiency and convergence parameters to establish a two-dimensional technology fusion system. Secondly, according to the characteristics of different fusion stages, we select the order parameters at each stage and establish order parameters function to determine the evolution trajectories of technology fusion. Finally, the fixed-point theory and the bifurcation theory are used to analyze the robustness of each stage, and the robust theorem at different technology fusion stages is proposed. The research results show: (1) We find that the characteristics analysis of technology fusion can divide the technology fusion process into three different stages, and the main characteristics of each stage as the order parameter can better reveal the evolution trajectory of technology fusion. (2) We find that the dynamics of technology fusion are caused by competition between the driving force and the dissipating force in the process of technology fusion. (3) We find that the dynamics of the technology fusion process may cause technology fusion to fall into chaos. (4) We find that by reasonably changing the relationship between the driving force and the dissipating force, the technology fusion process can be kept stable.

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Keywords Fusion of information technology and manufacturing technology · Dynamic modeling · Evolutionary analysis · Fixed-point theorem · Bifurcation theory · Robust analysis

1 Introduction

Technology fusion addresses the phenomenon of technology overlap, and Curran [1] defines it as the blurring of boundaries between discontinuous areas of science, technology, market, or industry. Although scholars have widely recognized the phenomenon of technological fusion, they have not yet formed a unified understanding of its concept. Nygren [2] defined technology fusion as the horizontal fusion of different technologies. That is, based on the purpose of creating new functions or new products, technologies in different fields absorbed each other to expand their professional skills. Jeong [3] defined technology fusion as a technology replacement and believed that when innovative products (services) had similar properties but higher cost-effective properties than current products (services), they had stable interchangeability between them. Liuz [4] believed that in most cases, the innovations of technology substitution depended on technological breakthroughs in other industries and technological substitution would gradually cause industrial integration. Lei [5] defined technology fusion as technology complementarity and believed that a large platform or system formed by multiple technologies would achieve the goals of improving productivity, reducing user costs, and enriching product feature through technology complementarity. Xiao [6] described technology fusion as technology integration and believed that technology integration was the complementary cooperation phenomenon of multiple technologies included in the innovation of technology integration. In addition, technology convergence, fusion, merging, cross-fertilization, and hybridization are all terms used to address the phenomenon of technology overlap. At present, technological convergence and technological fusion are mainly used, and some works of the literature distinguish the differences between them. However, this paper believes that they are consistent, and the unified term is called "Technology fusion." Technology fusion began to attract attention in the 1980s and even more in the 1990s when diffusion and overlaps among robotics, computing, and information and telecommunication technologies began to have a significant impact on the products and strategies of firms in several industries from information and communication technology (ICT) to consumer electronics, to mechatronics [7]. Since then, several fields have been characterized by fusion dynamics [8]. In recent years, with the rapid development of the new generation of information technology, such as IoT [9], cloud computing [10], and big data [11], there have been many noteworthy changes in recent innovation trends. The deep fusion of manufacturing technology and information technology has gradually become the main trend of technology fusion. For example, manufacturing grid (MGrid) [12], product-service systems (PSSs) [13], industrial PSSs(IPS2) [14, 15], cloud manufacturing (CMfg) [10], CPS (cyber-physical systems) [16], and CPPS (cyber-physical production systems) [17]. At present, China as a manufacturing country is in the dilemma of loss of cost advantage, weak international competitiveness, and low level of intelligence in the global value chain. Hence, China must constantly fuse manufacturing technology and information technology to improve the intelligence of manufacturing. However, through investigation, we found that in most areas of China, there are still serious problems in the development of manufacturing. The current problems in the manufacturing industry are mainly reflected in the low fusion degree of production technology and information technology, the low fusion degree of products and information technology, and the low fusion degree of information technology and company business. Therefore, if the Chinese manufacturing industry wants to break the existing status and realize the rapid development of the manufacturing industry, a proper understanding of the trajectories of technology fusion and the dynamics of the fusion process are critical in making policies, decisions, and plans in technology management [18]. More broadly, understanding technology fusion dynamics could be informative for the definition of science and technology policies, by enabling comparison among investments and other forms of support for interdisciplinary areas, with support for existing domains [19].

To explore the trajectories and dynamics process of technology fusion, qualitative analysis including theoretical analysis, case studies and quantitative analysis including taxonomies, and data analysis have been proposed. However, the prediction results of qualitative analysis lack rigorous scientific analysis and the uniform standards, quantitative analysis are faced with shortcomings such as difficulty in data collection and the interpretation of data results. In addition, they all lack a dynamic analysis of the evolution process of technological fusion. Hence, there is no systematic empirical evidence on the overall characteristics of technology fusion. Complex system theory can reveal the trajectories and dynamics of technology fusion through a nonlinear analysis of the technology fusion process. However, there are very little researches on complex system theory for technology fusion.

This article aims to fill this gap, and we propose data-driven modeling and nonlinear analysis methods. This method fully combines qualitative analysis and quantitative analysis and uses qualitative analysis to explain the results of quantitative analysis. Therefore, this method makes up for the shortcomings of difficult interpretation of quantitative analysis. In addition, the method can systematically describe the evolution trajectories of the fusion system and the dynamics of the evolution process. First, we introduce technical efficiency and convergence parameters to establish a two-dimensional staged model and then select the order parameters to establish the corresponding order parameter equation. The order parameter equation can determine the evolution direction of technology fusion at each stage. Second, we introduce robustness to describe the dynamics. By the fixed-point theory and the bifurcation theory, we can get the robustness of each stage. Through the above analysis, we can give systematic empirical evidence on the overall characteristics of technology convergence.

The article is organized as follows. Section 2 reviews the technology fusion literature. Section 3 analyzes the fusion of manufacturing technology and information technology. Section 4 analyzes the dynamic fusion mechanism of manufacturing technology and information technology. Section 5 analyzes the robustness of technology fusion. Section 6 provides case analysis. Section 7 discusses the advantages and disadvantages of this research. Section 8 concludes the article.

2 Research background

The related research methods of fusion trajectories and dynamics are mainly divided into two categories, one is qualitative analysis methods, and the other is quantitative analysis. Table 1 presents the classification of related research methods and their main advantages and disadvantages.

2.1 Qualitative analysis method of technology fusion

The qualitative analysis methods of technology fusion mainly include technology roadmap, Delphi method, and case study method. The technology roadmap can also use the Delphi method. (1) Technology roadmap [29] was first used in enterprise technology management. The application of technology roadmap in technology fusion research is mainly to predict the development trajectories of fusion technology through expert knowledge [30]. (2) Delphi method [31] is also known as an expert opinion method or expert letter inquiry survey method. The original purpose is to obtain the most reliable consensus opinion from a group of experts through a series of intensive questionnaire surveys and controllable feedback. The application of the Delphi method in technology fusion is mainly to obtain the consensus opinions of experts on the trajectories of technology fusion [33]. (3) Case analysis [32] refers to the method of analyzing a single object in combination with literature and obtaining general and universal laws of things. The application of case analysis in technology fusion is mainly to comprehensively analyze multiple factors of technology development and draw the dynamic development trajectories of technology fusion [34].

2.2 Quantitative analysis methods of technology fusion

The quantitative analysis methods of technology fusion mainly include statistical analysis, co-occurrence analysis, cluster analysis, citation analysis, input–output analysis, and big data analysis. (1) Statistical Analysis. Due to the complexity of technology fusion, Keungoui [35] proposed correlation analysis indicators. These indicators can be used for statistical analysis and presentation and can also be further enriched for correlation analysis from different

Table 1 Analysis of existing research methods

	Analytical method	Advantage	Disadvantage
Qualitative analysis method	Technology roadmap (Hsi-Peng 2018) [20]	It can fully tap the invisible knowledge of technology fusion	The cost is high, the standard is difficult to unify
	Delphi method (Sungchu 2015) [21]	It can help enterprises make group decisions	High cost and lack of rigorous scientific analysis of prediction results
	Case study (Hyun 2010) [22]	It can fully explore the various influencing factors of the fusion process with sufficient details	The material collection is more difficult
Quantitative analysis method	Statistical analysis (Lukas 2019) [23]	Indicators are easy to understand	Obtaining indicator data is relatively difficult
	Co-occurrence analysis (Jeong 2014) [24]	It can reflect the connections between technologies, and the situation of cooperation. Also, it can refine invisible thematic connections	The impact of different classification schemes is uncertain, and the results depend on the accuracy of the classification itself. Also, data cleaning is more difficult, and keyword cleaning is more difficult
	Cluster analysis (Yuan 2019) [25]	The method is more flexible, you can freely choose the clustering angle and the clustering method. Also, it can discover the implicit association	Difficulty in interpreting cluster results
	Citation analysis (Juram 2019) [26]	It can reflect the implicit correlation of factors affecting technology fusion	The citation data itself is relatively scarce and the data set construction is difficult
	Input–output analysis (XING 2011) [27]	It can discover the influencing factors of fusion	Data collection and result interpretation are difficult
	Big data analysis (Alejandro 2019) [28]	It is suitable for large-scale data analysis and can discover the key factors of technology fusion	Interpretation of results is difficult

perspectives. (2) Co-occurrence analysis. Fusion analysis shows that if a common content or form feature frequently appears in the same literature at the same time, it often indicates that the two features are closely related. In the research of technology fusion, scholars mainly conduct co-occurrence analysis from the perspectives of classification, patentees, and subject terms. Co-classification analysis has been widely used in technology fusion-related research [36]. (3) Cluster analysis mainly uses clustering technology to group data into different sub-categories according to technical fields. It is usually combined with co-occurrence analysis, citation analysis, and text mining analysis. The application of cluster analysis in technology fusion research is mainly to cluster co-occurrence matrix by subject or technology classification to discover the main fusion fields [37]. (4) Citation analysis refers to the analysis of the citation of the target patent and the citation of the target patent. Wei [38] used patent citation analysis to conduct empirical research on discoveries in the early stage of technology fusion to explore the direction of technology fusion. (5) Input–output analysis [39] is the principle and method of analyzing the quantitative dependence between input and output in a specific economic system. Input–output analysis can be used to discover the quantitative effects of different influencing factors in technology fusion research [40]. (6) Big data analysis is suitable for massive data analysis and can discover the key factors and fusion trends of technology fusion from the whole field data set [41]. Among them, affected by the difficulty of data set construction and analysis index data calculation, citation analysis and input–output analysis methods have poor applicability in large-scale data sets and are mainly suitable for a specific problem/field or smaller data sets.

It can be seen from the above analysis that the current research on technology fusion has made great progress, but there are still shortcomings: (1) Lack of research on technology fusion from a systematic perspective. (2) Insufficient reflection on the dynamics of the trajectories of technology fusion. Therefore, only by adopting a system perspective can we more accurately and comprehensively understand and master the operating mechanism and dynamic characteristics of technology fusion. Evolutionary economics [42] took technology fusion as a link in a complex fusion process, and it emphasized the important role of competition, growth, resource constraints, and complex interdependencies in the fusion process. Therefore, based on the above evolutionary economic theory, Zhu [43], from the perspective of quality management, established a dynamic model to find out the internal evolution mechanism of technology fusion. Their research found the chaos effect in the process of technology fusion and then proposed a chaos control method to help enterprises continue to push technology fusion. Also, Zhu et al. [44] took technical efficiency as a measure of technology fusion to establish a technical efficiency evolution model and used convergence theory to discuss the evolution mode of technical efficiency in the three stages of technology fusion. The results showed that convergence intensity can effectively improve the performance of enterprises. But [43] did not conduct a phased study of technology fusion. Although [44] studied on technology fusion by different stages, the focus of the research was on technology convergence and there was no comprehensive research on technology fusion. Therefore, the research in this article can make up for these shortcomings.

The novel aspects of our research are as follows: (1) Using technical efficiency as an indicator to measure the different stages of technology fusion and convergence parameters as an indicator to measure the degree of technology integration and collaborative development, from a system modeling perspective, this paper constructs nonlinear dynamic models to quantitatively the process of technology fusion and reveals the complexity and dynamics of technology fusion, which overcomes the current research limitations represented by the qualitative analysis of the technology fusion. (2) To assess the robustness of the technology fusion, this paper uses the synergetic theory to extract the order parameters of the above nonlinear dynamic model and establishes the order parameter equation. And then this paper uses the fixed-point theorem and bifurcation theory to conduct a robust analysis of the order parameter equation and proposes the robust theorem of technology fusion at different stages. (3) From a robustness management perspective, this paper attempts to address the robustness of the technology fusion starting from the root causes, by selecting a reasonable investment to get a suitable technology development potential coefficient and determine favorable integration degree or collaborative development between manufacturing technology and information technology. The proposed method can reveal the trajectories and dynamics of technology fusion and offer a practical framework for managing the robustness of technology fusion, which facilitates the ex ante robustness-based design and the ex post robustness control of technology fusion.

3 Analysis of technology fusion between manufacturing technology and information technology

3.1 Interactive relationship between manufacturing technology and information technology

The two aspects of technology fusion in manufacturing enterprises are the integration of technologies and the dynamic collaborative development of technologies. In this paper, the technology fusion frame is mainly constructed by the development of different technologies and the integration and collaborative development of different technologies.

As shown in Fig. 1, on the one hand, the application of information technology promotes the enterprise's manufacturing skills and management intelligence, help enterprises improve management efficiency, customer satisfaction, productivity and competitiveness and reduce operating cost, optimize production structure. On the other hand, in addition to the mutual promotion of internal manufacturing technology and information technology, the development and progress of internal technology are inevitably affected by the environmental. The introduction of external new technologies will inevitably drive internal technological progress. Under the circular effect of the internal and external technical environment, the manufacturing technology and information technology of the enterprise are continuously improved and updated.

It is worth noting that based on research needs, we abstract manufacturing technology and information technology for discussion. However, manufacturing technology and information technology are inseparable in practice. Many manufacturing technologies are integrated with information technology, but this is the root of fusion and the main reason we discuss technology fusion. That is to say, the manufacturing technology fused with information technology is still manufacturing technology, and the information technology of this paper includes information technology that has not been integrated with manufacturing technology, such as software technology and numerical control technology. Or information technology that can only exist independently, such as communication technology and information system, and their fusion with manufacturing technology mainly focuses on matching and cooperation.

Technology fusion stems from technological change and the emergence of new technologies [45]. Its main driving forces include rule breaking, product binding, and technology integration that integrates multiple products into systems. The role of rule breaking in promoting technology integration is reflected: Legal changes will lead to huge changes in market size and potential application of new technologies, which will disrupt existing rules. The results are mainly reflected in two aspects: First, R & D enterprises that have substitute technology in this industry and those enterprises in other industries that can directly apply technology to this industry join the competition and share market share. Second, lower customer switching costs and prolonged price wars destroy existing profit margins, thereby changing rules and disintegrating the internal structure of the industry. The role of product binding in promoting technology integration is reflected: The technical improvement of a product or platform will cause the enterprise to accelerate the improvement and innovation of complementary products to maintain its competitive advantage. The product binding strategy

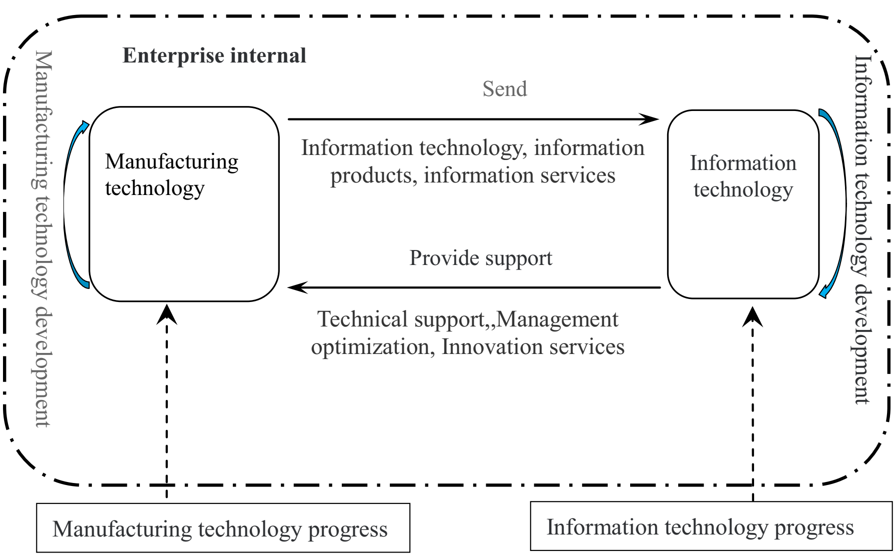


Fig. 1 Dynamic integration and collaborative development model. Figure from Ref. [44]

helps companies apply similar production processes to provide products and services to form economies of scale and cost-effectiveness, while increasing brand equity and differentiated competitive advantages. Also, the complexity of integrated systems has enabled companies to adopt technology diversification strategies to improve their technical experience and capabilities, so that integrated systems have an impact on the development of multiple industries from both the decentralized and integrated technologies.

3.2 The content and method of technology fusion between manufacturing technology and information technology

The manufacturing technology in this paper is a broad manufacturing technology, including the technology involved in the process from product production to sale. The information technology in this paper includes hardware technology, software technology, network technology, information security technology, information standardization technology, database technology, etc.

The fusion of manufacturing technology and information technology is the fusion of information technology with manufacturing technology, to achieve the global optimization of the entire manufacturing system, which not only exerts the overall benefits of manufacturing technology, but also reflects the huge advantages of information technology. The overall operation of a manufacturing enterprise includes four main functions: product design, product manufacturing, supply and marketing services, and decision management. These four functions provide a solid guarantee for the good operation of various tasks of the enterprise. Therefore, the fusion of manufacturing technology and information technology is mainly reflected in product design informatization, product manufacturing informatization, supply and marketing service informatization, enterprise management informatization, as shown in Fig. 2. In terms of product design, combining computer technology to improve the design accuracy and efficiency of products, to ensure the quality of products, and to lay a solid foundation for the smooth development of subsequent work, information technology in product design includes CAD, CAE, CAPP, CAM, PDM, DFX tools, and computer-aided innovative design (CAI), etc. In terms of product manufacturing, the fusion of information technology and manufacturing technology is reflected in digital equipment, including CNC machine tools, machining centers, etc. Currently, the fusion help enterprises improve the level of automation in the product manufacturing process, improve product manufacturing accuracy and efficiency, and ensure the smooth connection of the upper and lower processes. In terms of supply and marketing services, the fusion is reflected in the combination of information technology and modern management methods to improve the sales capacity and service quality. Currently, information technology includes CRM, SCM, EC, etc., which realizes the optimization of the entire operational process of the enterprises strategically and tactically. In enterprise decision management, fusion is reflected in the enterprise management platform. Through this platform, it helps enterprises to manage and regulate various activities in a unified manner, improve the processing quality of products in various tasks, and achieve overall efficient and coordinated operation. Currently, information technology includes the application of ERP methods in enterprise management. Through the feedback of logistics, information flow, and capital flow, it integrates the needs of customers with the internal production and operation activities of the enterprise and the resources of suppliers and is a brand-new management method that carries out business management completely according to user needs.

4 Analysis of the dynamic fusion mechanism of manufacturing and information technologies

4.1 Mathematical modeling

Basic assumptions and definitions of the model

Hypothesis 1 There is no significant change in the scale of production factors during the period of technological integration and collaborative development of enterprises.

Hypothesis 2 The convergence parameters of technology are directly proportional to the gap of technology efficiency between manufacturing technology and information technology.

Definition 1 The technology efficiency development potential coefficient refers to the maximum

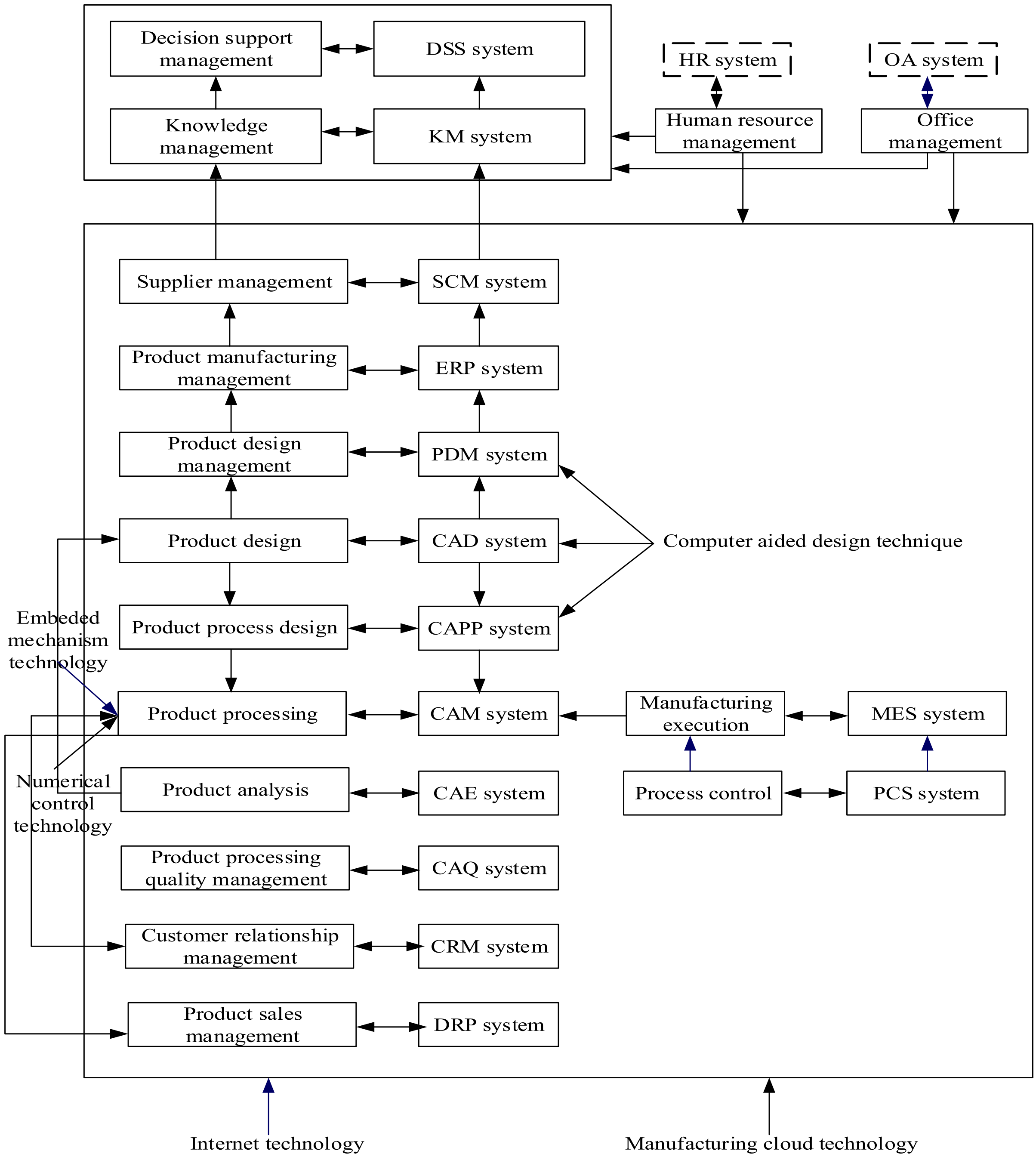


Fig. 2 Fusion of manufacturing technology and information technology. Figure from Ref. [45]

acceleration of the technology efficiency through investment means.

Definition 2 Technology integration refers to a method of creating new technologies with unified overall functions by reorganizing manufacturing technology and information technology according to certain technical principles or functions. It can often achieve the purpose of technical requirements that cannot be achieved by a single technology.

Definition 3 Technology collaborative development refers to manufacturing technology and information technology cooperating to complete a certain goal and achieve a win–win result of common development.

The purpose of technology integration is to create innovative technology to complete tasks that cannot be accomplished by a single technology. For manufacturing enterprises, a new technology is mature and brings technical efficiency to the enterprise only after the technologies are completely integrated. Otherwise, the incomplete integration of technology will cause a waste of two technical resources, not only will not improve the technical efficiency but will cause the technical efficiency to decline. Therefore, the technology will inhibit the improvement of technical efficiency in the stage of incomplete integration. The purpose of the collaborative development of technology is that the two technologies will cooperate with each other to complete the manufacturing task after complete integration and promote the development of the two technologies and the improvement of technical efficiency. Therefore, the collaborative development of technologies will promote the improvement of the efficiency of the two technologies. Also, enterprises will promote the development of technology efficiency through the introduction of new manufacturing technology and information technology. However, due to the limited resources of enterprises and the complexity of the manufacturing environment, therefore, manufacturing enterprises will be hindered in the process of technology fusion.

The details of the model are as follows:

1. $\alpha_1 - \beta_1 x(t)$ represents the growth rate of information technology efficiency. The parameter α_1 represents the maximum development potential coefficient of information technology efficiency, and it represents the maximum growth rate of information technology efficiency when the manufacturing enterprise independently develops information technology and the current production factor input structure remains unchanged.$\beta_1 x(t)$ represents the obstacles to the development of information technology efficiency at the current level of information technology.
2. $\gamma_1 x(t)y(t)$ represents the impact of the collaborative development of technologies on the improvement of information technology efficiency. The parameter γ_1 represents the convergence parameter of information technology to manufacturing technology and satisfies $-1 \leq \gamma_1 \leq 1$. $-1 \leq \gamma_1 \leq 0$ represents that information technology to manufacturing technology from complete nonintegration to complete integration. $\gamma_1 = -1$ represents complete nonintegration, and $\gamma_1 = 0$ represents complete integration. $0 \leq \gamma_1 \leq 1$ represents that information technology to manufacturing technology from complete integration to fully collaborative development. $\gamma_1 = 1$ represents fully collaborative development.
3. $\alpha_2 - \beta_2 x(t)$ represents the growth rate of manufacturing technology efficiency. The parameter α_2 represents the maximum development potential coefficient of manufacturing technology efficiency, and it represents the maximum growth rate of manufacturing technology efficiency when the manufacturing enterprise independently develops manufacturing technology and the current production factor input structure remains unchanged. $\beta_2 x(t)$ represents the obstacles to the development of manufacturing technology efficiency at the current level of manufacturing technology.
4. $\gamma_2 x(t)y(t)$ represents the impact of the collaborative development of technologies on the improvement of manufacturing technology efficiency. The parameter γ_2 represents the convergence parameter of manufacturing technology to information technology and satisfies $-1 \leq \gamma_2 \leq 1$. $-1 \leq \gamma_2 \leq 0$ represents that manufacturing technology to information technology from complete nonintegration to complete integration.$\gamma_2 = -1$ represents complete nonintegration, $\gamma_2 = 0$ represents complete integration. $0 \leq \gamma_2 \leq 1$ represents that manufacturing technology to information technology from complete integration to complete collaborative development (Table 2). $\gamma_2 = 1$ represents complete collaborative development.

Therefore, based on the above analysis, we obtain the nonlinear dynamic model of the technology fusion system:

$$\begin{aligned} \frac{\mathrm{d}x}{\mathrm{d}t} &= \alpha_1 x - \beta_1 x^2 + \gamma_1 xy \\ \frac{\mathrm{d}y}{\mathrm{d}t} &= \alpha_2 y - \beta_2 y^2 + \gamma_2 xy \end{aligned} \tag{1}$$

Table 2 Notation and parameter values in the model

Notation	Explanation
$x(t)$	Information technology efficiency
$y(t)$	Manufacturing technology efficiency
α_1	Information technology efficiency development potential coefficient
α_2	Manufacturing technology efficiency development potential coefficient
β_1	Damping coefficient of information technology efficiency growth
β_2	Damping coefficient of manufacturing technology efficiency growth
γ_1	The convergence parameter of information technology to manufacturing technology
γ_2	The convergence parameter of manufacturing technology to information technology

4.2 Model parameter calculation

Definition 1 Each technology input proportion of the enterprise will correspond to the maximum output. Production frontier [46] refers to the boundary surface formed by the maximum output set corresponding to the different technology inputs proportion of the enterprise

Definition 2 Technology efficiency [44] is defined as the ratio between the actual output of the decision-making unit and the maximum output under the same amount of input of production factors.

In this paper, we use technology efficiency as a scalar to measure the level of two technologies. To distinguish between manufacturing technology and information technology, we use x to define information technology efficiency, and y to represent manufacturing technology efficiency.

Definition 3 Information Technology Production Factor Set X = {Interface and communication technology, database technology, integrated framework technology, software technology, artificial intelligence technology, expert system, decision support system, data standard, sensor and control technology, neural network technology}. Manufacturing Technology Production Factor Set Y = {Production automation technology, process design technology, product inspection technology, machine tool and tool technology, single-machine processing unit and process control technology, engineering technicians and management personnel training and education in various advanced production technologies and programs}.

For a more intuitive discussion, we use one-dimensional output, which is only a reduction in dimension and does not affect the conclusion. We use E to represent the set of production factors, $Q(E)$ to indicate the actual output corresponding to production factors E, and $Q^*(E)$ to indicate the output in production frontier corresponding to production factors E. Therefore, the technology efficiency of the manufacturing enterprise is defined as $\frac{Q}{Q^*}$ (Fig. 3).

Therefore information technology efficiency is defined $x = \frac{Q_{\text{information}}}{Q^*_{\text{information}}}$ and satisfies $x \le 1$. Manufacturing technology efficiency is defined $y = \frac{Q_{\text{manufacturing}}}{Q^*_{\text{manufacturing}}}$ and satisfies $y \le 1$.

Definition 4 Due to financial constraints and the complexity of the manufacturing environment, manufacturing enterprises' technical efficiency development process usually encounters some obstacles. This paper uses the damping coefficients β_1, β_2 of technical efficiency to represent the obstacles during the development of technical efficiency.

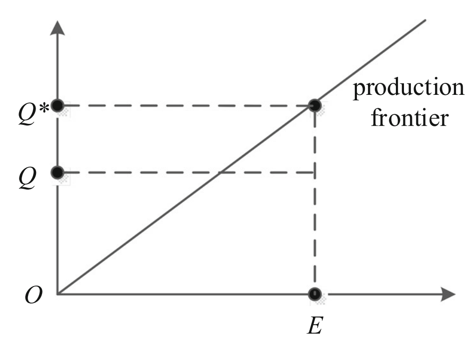


Fig. 3 Technical efficiency measurement route

$$\beta_1 = \frac{1}{2}\left[\frac{Q_{\text{information}}(k)}{Q^*_{\text{information}}(k)} - \frac{Q_{\text{information}}(k-3)}{Q^*_{\text{information}}(k-3)} - 3\left(\frac{Q_{\text{information}}(k-1)}{Q^*_{\text{information}}(k-1)} - \frac{Q_{\text{information}}(k-2)}{Q^*_{\text{information}}(k-2)}\right)\right],$$

$$\beta_2 = \frac{1}{2}\left[\frac{Q_{\text{manufacturing}}(k)}{Q^*_{\text{manufacturing}}(k)} - \frac{Q_{\text{manufacturing}}(k-3)}{Q^*_{\text{manufacturing}}(k-3)} - 3\left(\frac{Q_{\text{manufacturing}}(k-1)}{Q^*_{\text{manufacturing}}(k-1)} - \frac{Q_{\text{manufacturing}}(k-2)}{Q^*_{\text{manufacturing}}(k-2)}\right)\right].$$

At the same production level, if the production factor input ratio remains unchanged, the above calculation can be simplified to

$$\beta_1 = \frac{1}{2Q^*_{\text{information}}(k-3)}[Q_{\text{information}}(k) - Q_{\text{information}}(k-3) \\ -3(Q_{\text{information}}(k-1) - Q_{\text{information}}(k-2))],$$

$$\beta_2 = \frac{1}{2Q^*_{\text{manufacturing}}}[Q_{\text{manufacturing}}(k) - Q_{\text{manufacturing}}(k-3) \\ -3(Q_{\text{manufacturing}}(k-1) - Q_{\text{manufacturing}}(k-2))]$$

Notation For manufacturing enterprises, the damping coefficient is constant, which are affected by the complexity of the enterprise's manufacturing environment, etc.

Definition 5 The convergence parameters γ_1, γ_2 represent the matching degree of one technology to another technology, which are used to measure the degree of technology integration and collaborative development.

The essence of convergence is the process of low performance moving closer to high performance and high-performance releasing energy to low performance. Manufacturing technology and information technology infiltrate each other in the process of technology fusion. The low technical efficiency moves closer to the high technical efficiency, and the high technical efficiency releases energy to the low technical efficiency. Therefore, we regard the technology fusion process as a convergence process. According to the element attributes of convergence, it can be divided into homogeneous convergence and heterogeneous convergence. The convergence of elements with the same attributes is homogenous convergence; otherwise, it is heterogeneous convergence. This paper takes manufacturing technology and information technology as two types of technical analysis. In view of the difference in the way of action of information technology and manufacturing technology, the convergence of information technology and manufacturing technology belongs to two-dimensional heterogeneous convergence. To put the two-dimensional heterogeneous convergence on the same scale and simplify the two-dimensional convergence problem to one-dimensional convergence, we define "integration" and "collaborative Development" to describe the convergence process, so that the discussion of heterogeneous convergence can be attributed to unified. To describe the degree of convergence, we define convergence parameters, as shown in Fig. 4.

In this paper, we believe that a technology with a short R & D cycle can quickly satisfy the needs of another technology. Therefore, a technology with a short R & D cycle has a stronger matching ability and the convergence parameter is larger. According to assumption 2, we can get

$$\Delta x(k) = \gamma_1^k d(x(k-1))$$
$$\Delta y(k) = \gamma_2^k d(y(k-1)).$$

Therefore, the convergence parameters can be expressed as

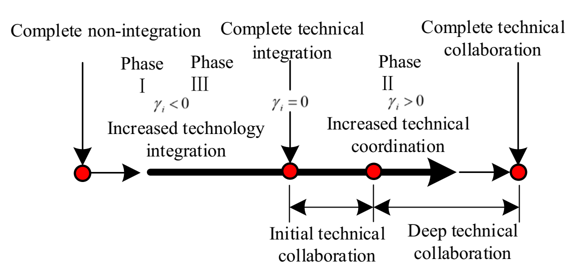


Fig. 4 Technology integration and collaborative development stage

$$\gamma_1^k = \frac{\Delta x(k)}{d(x(k-1))}$$
$$\gamma_2^k = \frac{\Delta y(k)}{d(y(k-1))}$$

where $\Delta x(k)$ represents the changes of information technology efficiency x at time k. $d(x(k-1))$ represents the distance between information technology x and manufacturing technology y at time $k-1$(The distance function in this paper is the gap between the two technical outputs). $\Delta y(k)$ represents the changes of manufacturing technology efficiency y at time k. $d(y(k-1))$ represents the distance between manufacturing technology y and information technology x at time $k-1$. γ_1^k is the convergence parameter of information technology efficiency at time k. γ_2^k is the convergence parameter of manufacturing technology efficiency at time k. Obviously, $\gamma_i^k(k=1,2)$ are ratio of changes to distance. In practical problems, $\gamma_{\mathrm{i}}^k(i=1,2)$ should be uncertain variables. For the convenience of calculation, we take the average of all moments on the same production frontier and treat them as constant:

$$\gamma_1 = \frac{\overline{\Delta x(k)}}{\overline{d(x(k\ -\ 1))}}$$
$$\gamma_2 = \frac{\overline{\Delta y(k)}}{\overline{d(y(k\ -\ 1))}}$$

Based on the above analysis, the convergence parameters are related to business investment in technology management, and the convergence parameters are constant if business investment for technology management is unchanged. Technology fusion is a gradual process of mutual penetration of manufacturing technology and information technology. According to technology integration and the collaborative development of technology, this paper specifies the convergence parameters $-1 \leq \gamma_1, \gamma_2 \leq 1$. When $-1 \leq \gamma_1, \gamma_2 \leq 0$, this stage is the technology integration stage. $\gamma_1 = -1$ represents that the integration of information technology and manufacturing technology is invalid, which is called complete nonintegration. $\gamma_1 = 0$ represents that technology integration is effective at this time, called complete technical integration. Complete technical integration means that the interaction of information technology and manufacturing technology will neither promote the efficiency of information technology nor inhibit its development. $0 < \gamma_1, \gamma_2 \leq 1$ represents technical collaborative development.$\gamma_1 = 1$ represents the synchronization of information technology and manufacturing technology. Currently, information technology and manufacturing technology are completely collaborative. Similarly, the definition of the convergence parameter of manufacturing technology can be obtained. The relationship between γ_1 and γ_2 is shown in Fig. 4.

Definition 6 The technology efficiency development potential coefficients α_1, α_2 indicate that the maximum possible development acceleration before reaching the production frontier when the current technical level remains unchanged.

$$\alpha_1 = 1 - \frac{Q_{\text{information}}(k-1)}{Q^*_{\text{information}}(k-1)}\frac{Q^*_{\text{information}}(k)}{Q_{\text{information}}(k)} + \beta_1\frac{Q_{\text{information}}(k)}{Q^*_{\text{information}}(k)} - \gamma_1\frac{Q_{\text{manufacturing}}(k)}{Q^*_{\text{manufacturing}}(k)}$$
$$\alpha_2 = 1 - \frac{Q_{\text{manufacturing}}(k-1)}{Q^*_{\text{manufacturing}}(k-1)}\frac{Q^*_{\text{manufacturing}}(k)}{Q_{\text{manufacturing}}(k)} + \beta_2\frac{Q_{\text{manufacturing}}(k)}{Q^*_{\text{manufacturing}}(k)} - \gamma_2\frac{Q_{\text{information}}(k)}{Q^*_{\text{information}}(k)}$$

By definition, we can know that the technology efficiency development potential coefficients α_1, α_2 are related to the production frontier. When the production frontier does not change, the technology efficiency development potential coefficients will not change. Therefore, in the same production frontier, if the input ratio of production factors remains unchanged, the maximum output Q^* at different times remains unchanged, and the above calculation can be simplified as

$$\alpha_1 = 1 - \frac{Q_{\text{information}}(k-1)}{Q_{\text{information}}(k)} + \beta_1\frac{Q_{\text{information}}(k)}{Q^*_{\text{information}}} - \gamma_1\frac{Q_{\text{manufacturing}}(k)}{Q^*_{\text{manufacturing}}}$$
$$\alpha_2 = 1 - \frac{Q_{\text{manufacturing}}(k-1)}{Q_{\text{manufacturing}}(k)} + \beta_2\frac{Q_{\text{manufacturing}}(k)}{Q^*_{\text{manufacturing}}} - \gamma_2\frac{Q_{\text{information}}(k)}{Q^*_{\text{information}}}$$

In addition, to facilitate calculation, we just take the average value of the technology efficiency development potential coefficients on the same production frontier.

Due to the short development cycle of information technology, the development of information technology is always ahead of manufacturing technology. Furthermore, for manufacturing, the R & D and introduction of information technology are mainly to support the current manufacturing technology and improve the manufacturing informatization and automation of manufacturing enterprises. Therefore, the convergence rate of information technology to manufacturing technology is always faster than the convergence rate of manufacturing technology to information technology, so we can obtain $\gamma_1 > \gamma_2$.

4.3 Order parameter analysis of dynamic model of enterprise fusion

The enterprise technology fusion system is an open and complex system. To pursue efficiency and produce products that meet the needs of consumers, enterprises need to continuously invest resources to carry out technological fusion. Therefore, the investment of resources by enterprises forms the driving force for the development of technology fusion. However, the limited internal resources of the enterprise and the restrictions of the social environment will form the dissipating force to inhibit the development of enterprise technology fusion. The enterprise technology fusion system will go through various stages of the life cycle in the process of competition between the driving force and the dissipating force and may fall into chaos.

For manufacturing enterprises, the technology fusion generally consists of the following three stages. *Stage I*: Manufacturing technology efficiency is greater than information technology efficiency. Manufacturing enterprises can introduce new information technology through investment, which changes the production frontier of information technology, i.e., α_1 changed. When information technology efficiency satisfies $|x - y_{10}| \leq \delta$, it shows that the information technology of enterprises no longer lags behind the manufacturing technology. At this time, technology fusion can enter stage II. *Stage II*: Manufacturing technology efficiency and information technology efficiency satisfy $|x - y| \leq \delta$, manufacturing enterprises invest a lot of manpower, material and financial resources to improve the technology management level, so that the current technology management level can make full use of technology and improve the integration of technology or technology collaborative development. Furthermore, the fusion of information technology and manufacturing technology will be improved to greatly improve the technical efficiency of enterprises. At this time, information technology and manufacturing technology may appear in two situations: (1) When the information technology efficiency and the manufacturing technology efficiency satisfy $x - y > \delta$, it means that the information technology in the enterprise has been ahead of the manufacturing technology. At this time, the technology fusion can enter stage III. *Stage III*: Information technology efficiency is higher than manufacturing technology efficiency, and the lagging development of manufacturing technology has become the bottleneck of technological fusion. Therefore, manufacturing enterprises will turn their attention to the introduction of new manufacturing technology to improve α_2. When information technology efficiency satisfies $|y - x_{30}| < \delta$, it shows that the manufacturing technology of the enterprise no longer lags behind the information technology; at this time, technology fusion can enter stage II. (2) When information technology efficiency and manufacturing technology efficiency satisfy $y - x > \delta$, it shows that the manufacturing technology of the enterprise has been ahead of the information technology, and technology fusion can enter stage I, where δ represents the maximum technology efficiency error when manufacturing technology and information technology match.y_{10} represents the initial manufacturing technical efficiency of stage I. x_{30} represents the initial information technical efficiency of stage III.

Notation In this paper, the fusion process is consisted of two parts: integration and collaboration development.

The dominant state variable is called the order parameter in the synergy theory [47]. Therefore, according to the above three stages, we give the order parameters and order parameter equations of the above three stages:

(1) *Stage I* At this stage, the manufacturing technology level of enterprises is higher than that of information technology. Therefore, manufacturing enterprises will invest manpower, material, and financial resources to improve information technology, so that manufacturing technology and information technology will continue to match. Therefore, the investment and development of manufacturing technology at this stage is almost zero, and information technology has received a lot of investment and development. Therefore, information technology has become the decisive factor for the development of technology fusion, that is, the order parameter. According to the adiabatic elimination method, the change rate of manufacturing technology efficiency is 0:

$$\begin{aligned}\frac{dx}{dt} &= \alpha_1 x - \beta_1 x^2 + \gamma_1 xy \\ \frac{dy}{dt} &= \alpha_2 y - \beta_2 y^2 + \gamma_2 xy = 0\end{aligned} \tag{2}$$

If current manufacturing technology efficiency $y \neq 0$, above Eq. (1) can be simplified to the following order parameter equation:

$$\begin{aligned}\frac{dx}{dt} &= \left(\alpha_1 + \frac{\gamma_1 \alpha_2}{\beta_2}\right)x + \left(\frac{\gamma_1 \gamma_2}{\beta_2} - \beta_1\right)x^2 \\ y &= \frac{\alpha_2 + \gamma_2 x}{\beta_2}\end{aligned} \tag{3}$$

To reveal as much as possible the fusion law of manufacturing technology and information technology, Eq. (3) is discretized as:

$$x(t+1) = \left(\alpha_1 + \frac{\gamma_1 \alpha_2}{\beta_2} + 1\right)x(t) + \left(\frac{\gamma_1 \gamma_2}{\beta_2} - \beta_1\right)x^2(t) \tag{4}$$

In the development of information technology $x(t+1) = \left(\alpha_1 + \frac{\gamma_1 \alpha_2}{\beta_2} + 1\right)x(t) - \left(\beta_1 - \frac{\gamma_1 \gamma_2}{\beta_2}\right)x^2(t)$, $\left(\alpha_1 + \frac{\gamma_1 \alpha_2}{\beta_2} + 1\right)x(t)$ represents the driving force, that is, a force that changes the efficiency of the original information technology, and $\left(\beta_1 - \frac{\gamma_1 \gamma_2}{\beta_2}\right)x^2(t)$ means dissipating force. When the Information Technology Efficiency Development Potential Coefficient α_1 is small, the driving force is less than the dissipating force, and $x(t)$ can only tend to a steady state. When α_1 gradually increases, the driving force changes from small to large, and a period-doubling bifurcation behavior will occur as shown in Fig. 5. When the driving force and the dissipating force are equal, chaos occurs. Therefore, enterprises will face two difficulties in the process of information technology fusion: (1) If an enterprise continues to improve information technology, due to the fierce competition between the driving force and the dissipative force, the development of enterprise information technology will begin to fluctuate until it falls into chaos. (2) However, if the enterprise does not improve information technology, that will make the product informatization low, leading to the entry of substitutes into the market and encroaching on the market share of the enterprise. At this time, the driving force is significantly less than the dissipating force; if the enterprise does not reform in time, the enterprise will eventually become bankrupt. Therefore, when an enterprise is improving

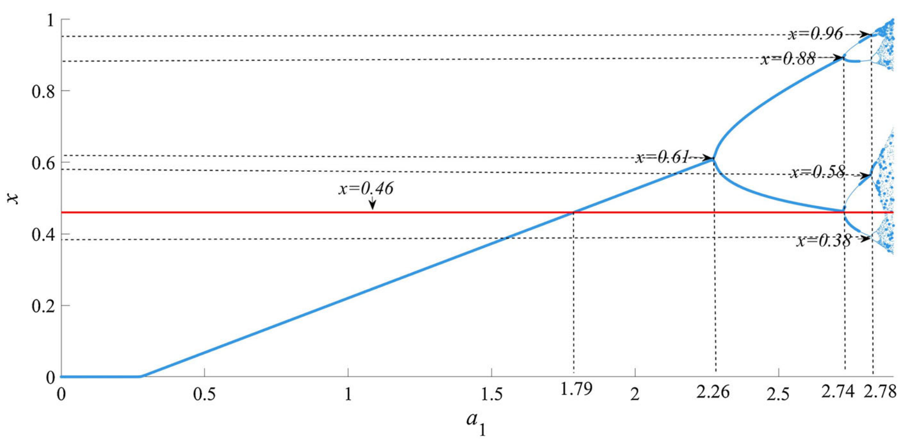


Fig. 5 Information technology efficiency evolution analysis ($\gamma_1 = -0.4, \gamma_2 = -0.5$)

information technology, managers must timely judge the relationship between the driving force and the dissipating force of the enterprise. Before the information technology development falls into chaos, the information technology development system should be forced to enter stage II.

(2) *Stage II* At this stage, the manufacturing technology level of the manufacturing enterprises is consistent with the information technology level. Therefore, manufacturing enterprises will invest to improve the technical integration and collaborative development of information technology and manufacturing technology. Therefore, manufacturing technology and information technology at this stage are decisive factors for the development of manufacturing enterprises, that is, order parameters. Therefore, according to Eq. (1), the fusion law of manufacturing technology and information technology can be expressed as:

$$\begin{aligned} x(t+1) &= (\alpha_1+1)x(t) - \beta_1 x^2(t) + \gamma_1 x(t)y(t) \\ y(t+1) &= (\alpha_2+1)y(t) - \beta_2 y^2(t) + \gamma_2 x(t)y(t) \end{aligned} \tag{5}$$

Before the driving force and dissipating force of the information technology development are equal, the enterprise should change the resource investment strategy to make the information technology development enter a new stage II: the fusion development of manufacturing technology and information technology. At this stage, the investment strategy of the enterprise should increase the degree of fusion γ_1, γ_2 of the two technologies through resource investment, thereby increasing the driving force of the technology fusion system and enabling the continuous development of enterprise technology fusion. And before the driving force and the dissipating force are equal, the enterprise should enter a new phase of development.

(3) *Stage III* With the continuous development of the industrial Internet of Things, industrial big data technology, etc., the information technology of manufacturing enterprises is gradually higher than that of manufacturing technology. Therefore, manufacturing enterprises will invest manpower, material resources, and financial resources to improve manufacturing technology. Therefore, the investment and development of information technology at this stage is almost zero and the manufacturing technology has received a lot of investment and development. Therefore, manufacturing technology has become a decisive factor for the development of technology fusion, that is, order parameters. According to the adiabatic elimination method, the change rate of information technology efficiency is 0:

$$\begin{aligned} \frac{\mathrm{d}x}{\mathrm{d}t} &= \alpha_1 x - \beta_1 x^2 + \gamma_1 xy = 0 \\ \frac{\mathrm{d}y}{\mathrm{d}t} &= \alpha_2 y - \beta_2 y^2 + \gamma_2 xy \end{aligned} \tag{6}$$

If current information technology efficiency $x \neq 0$, above Eq. (1) can be simplified to the following order parameter equation

$$\begin{aligned} \frac{\mathrm{d}y}{\mathrm{d}t} &= \left(\alpha_2 + \frac{\gamma_2\alpha_1}{\beta_1}\right)y + \left(\frac{\gamma_1\gamma_2}{\beta_1} - \beta_2\right)y^2 \\ x &= \frac{\alpha_1 + \gamma_1 y}{\beta_1} \end{aligned} \tag{7}$$

To reveal as much as possible the fusion law of manufacturing technology and information technology, Eq. (7) is discretized as:

$$y(t+1) = \left(\alpha_2 + \frac{\gamma_2\alpha_1}{\beta_1} + 1\right)y(t) + \left(\frac{\gamma_1\gamma_2}{\beta_1} - \beta_2\right)y^2(t) \tag{8}$$

In the development of manufacturing technology $y(t+1) = \left(\alpha_2 + \frac{\gamma_2\alpha_1}{\beta_1} + 1\right)y(t) - \left(\beta_2 - \frac{\gamma_1\gamma_2}{\beta_1}\right)y^2(t)$, $\left(\alpha_2 + \frac{\gamma_2\alpha_1}{\beta_1} + 1\right)y(t)$ represents the driving force, that is, a force that changes the efficiency of the original manufacturing technology, and $\left(\beta_2 - \frac{\gamma_1\gamma_2}{\beta_1}\right)y^2(t)$ means dissipating force. When the Manufacturing Technology Efficiency Development Potential Coefficient α_2 is small, the driving force is less than the dissipating force, and $y(t)$ can only tend to a steady state. When α_2 gradually increases, the driving force changes from small to large, and a period-doubling bifurcation behavior will occur as shown in Fig. 19. When the driving force and the dissipating force are equal, a situation in which the two forces compete with each other appears, that is, chaos occurs. Therefore, enterprises will face two difficulties in the process of manufacturing technology fusion: (1) If an enterprise continues to improve manufacturing technology, due to the fierce competition between the driving force and the dissipative force, the development of enterprise manufacturing technology will begin to fluctuate until it falls into chaos. (2) However, if the enterprise does not improve manufacturing technology, that will lead to low product productivity, high production cost, and low product quality, and will lead to the entry of substitutes into the market and encroaching on the market share of the enterprise. At this time, the driving force is significantly less than the dissipating force, and if the enterprise does not reform in time, the enterprise will eventually become bankrupt. Therefore, when an enterprise is improving manufacturing technology, managers must timely judge the relationship between the driving force and the dissipating force of the enterprise. Before the manufacturing technology development falls into chaos, the manufacturing technology should be forced to enter a new stage II.

5 Robustness analysis of dynamic model of enterprise technology fusion

Robustness originally means that the system can maintain its performance at a satisfactory level under the interference of internal and external environments. In recent years, the research on system robustness is mainly divided into the engineering field and the management field. The control system in the engineering field is a rigid system, which has strong anti-interference ability, and its sources of uncertainty have certain regularity and predictability [49–51]. However, the technology fusion system is a flexible system in the management field. Due to the influence of subjective and objective factors, its uncertainty is often random and difficult to predict. Therefore, the perspectives and methods of robustness research will also be different. Based on the above concept of robustness, this paper defines the robustness of the technology fusion system from two aspects: (1) stability of order parameters evolution trajectory of technology fusion system. It means that order parameters will temporarily deviate from a certain value when facing disturbance but will eventually return to this value automatically. (2) The final value of the evolution of the order parameter equation is not lower than the expected value of the manufacturing enterprises. According to the definition in this paper, we define the robustness of the technology fusion system into three categories: A robust state, if the values of the system order parameters are stable and higher than the expected value of enterprises. A weak robust state, if the values of the system order parameters are stable but not unique and all are higher than the expected value. A not robust state, if there is a value of the system order parameters that are unstable or lower than the expected value.

From the description in Sect. 3, the enterprise technology fusion system is a complex dynamic system with a dissipative structure. The enterprise needs to constantly change the technology development state to make the enterprise technology fusion cycle between different stages, to avoid the enterprise technology fusion from falling into chaos or stagnation. Therefore, the enterprise technology fusion system needs to enter the next state after the technology matures to avoid falling into chaos. In Sect. 4, through the definition of robustness, it can be known that by analyzing the robust evolution of technology fusion systems, it can help enterprises switch between different stages of technological fusion in time and avoid technological fusion from falling into chaos. Therefore, ensuring the robustness of the technology fusion system plays a vital role in the development of enterprise intelligence. It is also worth noting that the robust or weakly robust state of the technology fusion system is to ensure the stability of the technology fusion process at each stage from the early stage to the mature period, please refer to Fig. 26.

5.1 Robust analysis of stage I

Theorem 1 *When a manufacturing enterprise is developing information technology, if the information technology efficiency development potential coefficient satisfies:*

$$-\frac{\gamma_1\alpha_2}{\beta_2} < \alpha_1 < 2 - \frac{\gamma_1\alpha_2}{\beta_2}.$$

In addition, $\beta_1 > \frac{\gamma_1\gamma_2}{\beta_2}$ and $\frac{\alpha_1+\frac{\gamma_1\alpha_2}{\beta_2}}{\beta_1-\frac{\gamma_1\gamma_2}{\beta_2}} \geq x^*$. Then the technology fusion system of the enterprise is robust in the development stage of information technology, where x^* represents the enterprise expectation of information technology efficiency.

Proof According to Eq. (4), let

$$x_{t+1} = f(x_t) = \left(\alpha_1 + \frac{\gamma_1\alpha_2}{\beta_2} + 1\right)x_t + \left(\frac{\gamma_1\gamma_2}{\beta_2} - \beta_1\right)x_t^2.$$

We can obtain two fixed points of $x_{t+1} = f(x_t)$:

$$x_1 = 0, x_2 = \frac{\alpha_1 + \frac{\gamma_1\alpha_2}{\beta_2}}{\beta_1 - \frac{\gamma_1\gamma_2}{\beta_2}}.$$

According to the stability theorem, if x_1 is stable, it must satisfy

$$|f'(x)||_{x_1} = \left|\alpha_1 + \frac{\gamma_1\alpha_2}{\beta_2} + 1\right| < 1.$$

If x_2 is stable, it must satisfy

$$|f'(x)||_{x_2} = \left|\alpha_1 + \frac{\gamma_1\alpha_2}{\beta_2} + 1 + 2\left(\frac{\gamma_1\gamma_2}{\beta_2} - \beta_1\right)\frac{\alpha_1 + \frac{\gamma_1\alpha_2}{\beta_2}}{\beta_1 - \frac{\gamma_1\gamma_2}{\beta_2} - \beta_1}\right| < 1.$$

Therefore, according to the analysis, let $\begin{cases} |f'(x)||_{x_1} \geq 1 \\ |f'(x)||_{x_2} < 1 \end{cases}$, we can obtain the stable condition of x_2:

$$\begin{cases} \left|\alpha_1 + \frac{\gamma_1\alpha_2}{\beta_2} + 1\right| \geq 1 \\ \left|1 - \alpha_1 - \frac{\gamma_1\alpha_2}{\beta_2}\right| < 1 \end{cases}.$$

In other words, when $-\frac{\gamma_1\alpha_2}{\beta_2} < \alpha_1 < 2 - \frac{\gamma_1\alpha_2}{\beta_2}$, x_1 is unstable and x_2 stable. If $x_2 \geq x^*$, according to the definition of robustness in this paper, the technology fusion system is robustness when $-\frac{\gamma_1\alpha_2}{\beta_2} < \alpha_1 < 2 - \frac{\gamma_1\alpha_2}{\beta_2}$. Theorem 1 is verified.

Theorem 2 *When a manufacturing enterprise is developing information technology, if the convergence parameter of manufacturing technology satisfies* $\gamma_2 > -\frac{\alpha_2\beta_1}{\alpha_1}$, *when information technology convergence parameter satisfies* $\gamma_1 < \frac{\beta_1\beta_2}{\gamma_2}$, *by increasing the initial degree of information technology integration or collaborative development, the enterprise can effectively improve information technology efficiency in the development of information technology and reduce the investment cost of the enterprise.*

Proof : In the development stage of information technology, enterprises can effectively change the production frontier of information technology by introducing new information technology. The changes in production frontiers lead to changes in information technology efficiency development potential coefficient α_1. According to Theorem 1, when the information technology efficiency development potential coefficient satisfies $-\frac{\gamma_1\alpha_2}{\beta_2} < \alpha_1 < 2 - \frac{\gamma_1\alpha_2}{\beta_2}$, the technology fusion system is in a robust state, and the information technology efficiency is stable at $x = \frac{\alpha_1 + \frac{\gamma_1\alpha_2}{\beta_2}}{\beta_1 - \frac{\gamma_1\gamma_2}{\beta_2}}$. Now, when $\gamma_2 > 0$ and $\gamma_1 < \frac{\beta_1\beta_2}{\gamma_2}$, if γ_1 becomes bigger, $\alpha_1 + \frac{\gamma_1\alpha_2}{\beta_2}$ will become bigger and $\beta_1 - \frac{\gamma_1\gamma_2}{\beta_2}$ will become smaller; thus, $x = \frac{\alpha_1 + \frac{\gamma_1\alpha_2}{\beta_2}}{\beta_1 - \frac{\gamma_1\gamma_2}{\beta_2}}$ will become bigger. When $\gamma_2 < 0$ and $\gamma_1 > \frac{\beta_1\beta_2}{\gamma_2}$, we derive $x = \frac{\alpha_1 + \frac{\gamma_1\alpha_2}{\beta_2}}{\beta_1 - \frac{\gamma_1\gamma_2}{\beta_2}}$ about γ_1 and obtain $\frac{dx}{d\gamma_1} = \frac{\alpha_2\beta_1 - \alpha_1|\gamma_2|}{\beta_2\left(\beta_1 + \frac{\gamma_1|\gamma_2|}{\beta_2}\right)^2}$. Through the derivative function we can know that when $\gamma_2 > -\frac{\alpha_2\beta_1}{\alpha_1}$, $\frac{dx}{d\gamma_1} \geq 0$. That means that when γ_1 becomes bigger, $x = \frac{\alpha_1 + \frac{\gamma_1\alpha_2}{\beta_2}}{\beta_1 - \frac{\gamma_1\gamma_2}{\beta_2}}$ will become bigger. In summary, when $\gamma_2 > -\frac{\alpha_2\beta_1}{\alpha_1}$, if γ_1 becomes bigger,

$x = \frac{\alpha_1 + \frac{\gamma_1 \alpha_2}{\beta_2}}{\beta_1 - \frac{\gamma_1 \gamma_2}{\beta_2}}$ will become bigger. In addition, because γ_1 becomes bigger, $2 - \frac{\gamma_1 \alpha_2}{\beta_2}$ will decrease. Therefore, the change of the production frontier of the enterprise will be reduced compared with the original, and the investment of the enterprise will be reduced, which verifies Theorem 2.

Through the investment of information technology, enterprises change the production frontier of information technology; therefore, information technology development efficiency potential coefficient a_1 also changes. Stable promotion of technology fusion is very important for manufacturing enterprises, so enterprises should make information technology efficiency development potential coefficient a_1 change within a robust range $\left(-\frac{\gamma_1 \alpha_2}{\beta_2}, 2 - \frac{\gamma_1 \alpha_2}{\beta_2}\right)$. However, when $y_{10} - \frac{2}{\beta_1 - \frac{\gamma_1 \gamma_2}{\beta_2}} > \delta$, it means that if the information technology efficiency development potential coefficient a_1 of an enterprise changes in a robust interval, the technology fusion cannot enter stage II. Therefore, enterprises need to jump out of the current robust range of information technology efficiency development potential coefficient. Currently, x_2 is no longer stable. When the value of α_1 deviates slightly from $2 - \frac{\gamma_1 \alpha_2}{\beta_2}$, $\{x_t\}$ no longer converges to x_2, and two subsequences x_1^*, x_2^* will appear and satisfy $x_{2t} \to x_1^*, x_{2t+1} \to x_2^* (t \to \infty)$. That is, small changes of α_1 will lead to the development of information technology efficiency into two different development paths. Currently, the robustness of the evolution path of the technology fusion system in the development stage of information technology decreases. And as α_1 continues to change, there may be 4 times period bifurcation. At this time, if α_1 change a little at the 4 times period bifurcation point that will make the development of information technology efficiency appear 4 development paths, which makes the information technology efficiency robust lower than 2 times period. So with the increase of α_1, the period-doubling bifurcation will affect the robustness of the technology fusion system. Therefore, in the development of information technology, it is very important for the robust operation of manufacturing enterprises to master the period-doubling bifurcation point of the evolution of information technology efficiency. The following gives the algorithm for finding the period-doubling bifurcation point and the robust theorem of period-doubling evolution.

Theorem 3 *In the development stage of information technology, if the values* $x_1^*, x_2^*, \cdots x_{2^i}^*$ *are stable fixed points of information technology efficiency within* 2^i *times period and satisfy* $x_i^* \geq x^* (i = 1, 2, \cdots 2^i)$, *then the technology fusion system is weak robustness when* $b_{i-1} \leq \alpha_1 \leq b_i$, *where* b_{i-1} is 2^i *times period bifurcation point,* b_i *is* 2^i *times period bifurcation point.*

Theorem 4 *In the development stage of information technology, assuming the values* $x_1^*, x_2^*, \cdots x_{2^i}^*$ *are stable fixed points of information technology efficiency within* 2^i *times period, if there is* $x_i^* \in \{x_1^*, x_2^*, \cdots x_{2^i}^*\}$ *and satisfies* $x_i^* < x^* (i \in \{1, 2, \cdots 2^i\})$, *then the technology fusion system is not robust when* $b_{i-1} \leq \alpha_1 \leq b_i$. *According to self-similarity, if* $\alpha_1 > b_i$, *technology fusion is nonrobust.*

The following gives an algorithm for solving the period-doubling bifurcation point and judging the period-doubling evolution of information technology efficiency according to Theorems 3 and 4.

Algorithm1: Establishment of Robust Evolutionary Dynamic Model for SMISs

Input: The system parameter values $\alpha_1, \alpha_2, \beta_1, \beta_2, \gamma_1, \gamma_2$;

the minimum requirements of enterprises for information technology x_{10}.

Output: Robustness of dynamics model and bifurcation point of value α_1.

1: **Begin {**

2: $p = \frac{\gamma_1 \alpha_2}{\beta_2} + 1$; $q = \frac{\gamma_1 \gamma_2}{\beta_2} - \beta_1$.

3: $f(x) = (\alpha_1 + p)x + qx^2$.

4: **for** i=1 to N, where N is a given constant, $N = 5$ given in this paper. Generally speaking, $N > 5$ chaos appears.

5: $F(x) = f^{(2^i)}(x)$, where $f^{(2^i)}(x)$ represents 2^i compound operations on $f(x)$: $f^{(2^i)} = \underbrace{f(f(f(\cdots f(x))))}_{2^i}$.

6: $X_i = solve(F(x) = 0)$, where $X_i = \{x_1, x_2, \cdots x_{2^{2^i}}\}$ represents the set of solutions.

7: $Y_i = \{X_i^1, X_i^2, \cdots X_i^{C_{2^{2^i}}^{2^i}}\}$, where $X_i^j (j = 1,2 \cdots C_{2^{2^i}}^{2^i})$ represents the j-th subset composed of 2^i solutions selected from the solution set $X_i = \{x_1, x_2, \cdots x_{2^{2^i}}\}$.

8: **for** j=1 to $C_{2^{2^i}}^{2^i}$

9: **if** $|F'(x)| < 1$ for any $x \in X_i^j$ and $|F'(x)| \geq 1$ for any $x \in X_i^j / X_i^j$

10: $x \in X_i^j$ represents the set of all stable fixed points of the dynamic system, and get the 2^i times period bifurcation point b_i in the dynamic system.

11: **if** $x \geq x_{10}$ for any $x \in X_i^j$

12: The dynamic system is weak robustness in the interval $b_{i-1} < \alpha_1 < b_i$, where b_{i-1} is 2^{i-1} times period bifurcation point.

13： **else** The dynamic system is not robustness in the interval $b_{i-1} < \alpha_1 < b_i$

14： **end**

15： **else** continue

16: **end**

17: **end**

18: **end**

19: **return** The robustness of dynamic system and 2^i times period bifurcation point b_i

20：} **end**

5.2 Robust analysis of stage II

In Phase II, not considering the development of information technology and manufacturing technology, we mainly discuss how enterprises can increase the integration and the collaborative development of manufacturing technology and information technology through investment in technology management.

Theorem 5 *In the stage of technology integration and collaborative development, if information technology convergence parameter* γ_1 *and manufacturing technology convergence parameters* γ_2 *satisfy*

$$(\alpha_1\beta_1\beta_2 + \alpha_2\beta_1\gamma_1)(\alpha_2\beta_1\beta_2 + \alpha_1\beta_2\gamma_2) > (\alpha_2\beta_1\gamma_2 + \alpha_1\gamma_2^2)(\alpha_1\beta_2\gamma_1 + \alpha_2\gamma_1^2),\ \gamma_1\gamma_2 < \beta_1\beta_2.$$

Also

$$\frac{\alpha_1\beta_2 + \alpha_2\gamma_1}{\beta_1\beta_2 - \gamma_1\gamma_2} \geq x^*, \quad \frac{\alpha_2\beta_1 + \alpha_1\gamma_2}{\beta_1\beta_2 - \gamma_1\gamma_2} \geq y^*.$$

Then the technology fusion system is robust in the stage of technology integration and collaborative development, where y^* represents the enterprise expectation value of manufacturing technology efficiency.

Proof We calculate the fixed point of Eq. (5):

$$\begin{cases} \alpha_1 x - \beta_1 x^2 + \gamma_1 xy = 0 \\ \alpha_2 y - \beta_2 y^2 + \gamma_2 xy = 0 \end{cases}, \tag{8}$$

and obtain 4 fixed points

$$X_1(0,0), X_2(0,\frac{\alpha_2}{\beta_2}), X_3\left(\frac{\alpha_1}{\beta_1},0\right), X_4\left(\frac{\alpha_1\beta_2 + \alpha_2\gamma_1}{\beta_1\beta_2 - \gamma_1\gamma_2}, \frac{\alpha_2\beta_1 + \alpha_1\gamma_2}{\beta_1\beta_2 - \gamma_1\gamma_2}\right).$$

All other fixed points have a variable with zero technical efficiency except for X_4. Therefore, only X_4 can satisfy the needs of enterprises in this stage of technology integration and collaborative development. So, we only discuss the stability of X_4. Firstly, we construct the Jacobian matrix of $X_4(\frac{\alpha_1\beta_2+\alpha_2\gamma_1}{\beta_1\beta_2-\gamma_1\gamma_2}, \frac{\alpha_2\beta_1+\alpha_1\gamma_2}{\beta_1\beta_2-\gamma_1\gamma_2})$:

$$J_{X_4} = \begin{bmatrix} \frac{\partial f_1}{\partial x} & \frac{\partial f_1}{\partial y} \\ \frac{\partial f_2}{\partial x} & \frac{\partial f_2}{\partial y} \end{bmatrix} = \begin{bmatrix} \frac{\alpha_1\beta_1\beta_2 + \alpha_2\beta_1\gamma_1}{\gamma_1\gamma_2 - \beta_1\beta_2} & \frac{\alpha_1\gamma_1\beta_2 + \alpha_2\gamma_1^2}{\beta_1\beta_2 - \gamma_1\gamma_2} \\ \frac{\alpha_2\beta_1\gamma_2 + \alpha_1\gamma_2^2}{\beta_1\beta_2 - \gamma_1\gamma_2} & \frac{\alpha_2\beta_1\beta_2 + \alpha_1\beta_2\gamma_2}{\gamma_1\gamma_2 - \beta_1\beta_2} \end{bmatrix},$$

and obtain the characteristic equation of the above matrix

$$|\lambda E - J_{X_4}| = \lambda^2 - \frac{\alpha_1\beta_1\beta_2 + \alpha_2\beta_1\gamma_1 + \alpha_2\beta_1\beta_2 + \alpha_1\beta_2\gamma_2}{\gamma_1\gamma_2 - \beta_1\beta_2}\lambda + \frac{(\alpha_1\beta_1\beta_2 + \alpha_2\beta_1\gamma_1)(\alpha_2\beta_1\beta_2 + \alpha_1\beta_2\gamma_2) - (\alpha_2\beta_1\gamma_2 + \alpha_1\gamma_2^2)(\alpha_1\beta_2\gamma_1 + \alpha_2\gamma_1^2)}{(\gamma_1\gamma_2 - \beta_1\beta_2)^2} = 0 \tag{9}$$

By solving Eq. (9), two eigenvalues are obtained:

$$\lambda_1 = \frac{\beta_1(\alpha_1\beta_2 + \alpha_2\gamma_1) + \beta_2(\alpha_2\beta_1 + \alpha_1\gamma_2)}{2(\gamma_1\gamma_2 - \beta_1\beta_2)} + \frac{\sqrt{[\beta_1(\alpha_1\beta_2 + \alpha_2\gamma_1) - \beta_2(\alpha_2\beta_1 + \alpha_1\gamma_2)]^2 + 4\gamma_1\gamma_2(\alpha_1\beta_2 + \alpha_2\gamma_1)(\alpha_2\beta_1 + \alpha_1\gamma_2)}}{2|\gamma_1\gamma_2 - \beta_1\beta_2|}$$

$$\lambda_2 = \frac{\beta_1(\alpha_1\beta_2 + \alpha_2\gamma_1) + \beta_2(\alpha_2\beta_1 + \alpha_1\gamma_2)}{2(\gamma_1\gamma_2 - \beta_1\beta_2)} - \frac{\sqrt{[\beta_1(\alpha_1\beta_2 + \alpha_2\gamma_1) - \beta_2(\alpha_2\beta_1 + \alpha_1\gamma_2)]^2 + 4\gamma_1\gamma_2(\alpha_1\beta_2 + \alpha_2\gamma_1)(\alpha_2\beta_1 + \alpha_1\gamma_2)}}{2|\gamma_1\gamma_2 - \beta_1\beta_2|}$$

Now we let

$$\mathrm{I} = (\alpha_1\beta_1\beta_2 + \alpha_2\beta_1\gamma_1)(\alpha_2\beta_1\beta_2 + \alpha_1\beta_2\gamma_2) - (\alpha_2\beta_1\gamma_2 + \alpha_1\gamma_2^2)(\alpha_1\beta_2\gamma_1 + \alpha_2\gamma_1^2)$$
$$\Pi = \gamma_1\gamma_2 - \beta_1\beta_2,$$

we can obtain six situations:

Situation 1: If $\mathrm{I} = 0, \Pi > 0$, X_4 is unstable.
Situation 2: If $\mathrm{I} = 0, \Pi < 0$, X_4 is unstable.
Situation 3: If $\mathrm{I} > 0, \Pi > 0$, X_4 is unstable.
Situation 4: If $\mathrm{I} > 0, \Pi < 0$, X_4 is stable.
Situation 5: If $\mathrm{I} < 0, \Pi > 0$, X_4 is unstable.
Situation 6: If $\mathrm{I} < 0, \Pi < 0$, X_4 is unstable.

Through the above analysis, in the case of $X_4 > 0$, only Situation 4 satisfies the requirements of robustness, and the theorem is verified.

Theorem 6 *Enterprises in the stage of technology integration and collaborative development, when manufacturing technology convergence parameter $\gamma_2 < 0$, if $\alpha_2\beta_1 + \alpha_1\gamma_2 < 0$, increasing the gap Δ between the information technology convergence parameter and manufacturing technology convergence parameter will inhibit the improvement of the technology efficiency. However if $\alpha_2\beta_1 + \alpha_1\gamma_2 \geq 0$, increasing the gap Δ will promote the improvement of information technology efficiency. When manufacturing technology convergence parameter $\gamma_2 \geq 0$, increasing the gap Δ will promote the improvement of technology efficiency.*

Proof Enterprises invest in technology management to improve the integration and collaborative development of manufacturing technology and information technology; as a result, the information technology convergence parameter γ_1 and manufacturing technology convergence parameter γ_2 will be changed. According to Theorem 5, when the information technology convergence parameter and manufacturing technology convergence parameter satisfy

$$(\alpha_1\beta_1\beta_2 + \alpha_2\beta_1\gamma_1)(\alpha_2\beta_1\beta_2 + \alpha_1\beta_2\gamma_2) > (\alpha_2\beta_1\gamma_2 + \alpha_1\gamma_2^2)(\alpha_1\beta_2\gamma_1 + \alpha_2\gamma_1^2),$$

technology fusion system is in a robust state in the stage of technology integration and collaborative development and the technology efficiency is stable at

$$x = \frac{\alpha_1\beta_2 + \alpha_2\gamma_1}{\beta_1\beta_2 - \gamma_1\gamma_2}, \quad y = \frac{\alpha_2\beta_1 + \alpha_1\gamma_2}{\beta_1\beta_2 - \gamma_1\gamma_2}.$$

Because information technology develops faster than manufacturing technology, the information technology convergence parameter γ_1 is larger than the manufacturing technology convergence parameter γ_2, and the gap between γ_1 and γ_2 is generally constant ($\gamma_1 - \gamma_2 = \Delta$). Therefore, the stable value of technical efficiency can be expressed:

$$x = \frac{\alpha_1\beta_2 + \alpha_2(\Delta + \gamma_2)}{\beta_1\beta_2 - \Delta\gamma_2 - \gamma_2^2}, \quad y = \frac{\alpha_2\beta_1 + \alpha_1\gamma_2}{\beta_1\beta_2 - \Delta\gamma_2 - \gamma_2^2}.$$

Now, if $\gamma_2 < 0$, $\beta_1\beta_2 - \Delta\gamma_2 - \gamma_2^2$ will become bigger by increasing the gap Δ, hence $y = \frac{\alpha_2\beta_1 + \alpha_1\gamma_2}{\beta_1\beta_2 - \Delta\gamma_2 - \gamma_2^2}$ will decrease. In addition, we take derivation for $x = \frac{\alpha_1\beta_2 + \alpha_2(\Delta + \gamma_2)}{\beta_1\beta_2 - \Delta\gamma_2 - \gamma_2^2}$ about Δ, and we can obtain $\frac{dx}{d\Delta} = \frac{\beta_2(\alpha_2\beta_1 + \alpha_1\gamma_2)}{(\beta_1\beta_2 - \Delta\gamma_2 - \gamma_2^2)^2}$. When $\alpha_2\beta_1 + \alpha_1\gamma_2 < 0$, $\frac{dx}{d\Delta} < 0$. So we increase Δ, $x = \frac{\alpha_1\beta_2 + \alpha_2(\Delta + \gamma_2)}{\beta_1\beta_2 - \Delta\gamma_2 - \gamma_2^2}$ will decrease. When $\alpha_2\beta_1 + \alpha_1\gamma_2 \geq 0$, $\frac{dx}{d\Delta} \geq 0$. So we increase Δ, $x = \frac{\alpha_1\beta_2 + \alpha_2(\Delta + \gamma_2)}{\beta_1\beta_2 - \Delta\gamma_2 - \gamma_2^2}$ will increase.

If $\gamma_2 \geq 0$, increasing gap Δ,$\alpha_1\beta_2 + \alpha_2(\Delta + \gamma_2)$ will become bigger and $\beta_1\beta_2 - \Delta\gamma_2 - \gamma_2^2$ will become smaller, so $x = \frac{\alpha_1\beta_2 + \alpha_2(\Delta + \gamma_2)}{\beta_1\beta_2 - \Delta\gamma_2 - \gamma_2^2}$ will become bigger. Similarly $y = \frac{\alpha_2\beta_1 + \alpha_1\gamma_2}{\beta_1\beta_2 - \Delta\gamma_2 - \gamma_2^2}$ will become bigger. In summary, the theorem is verified.

In stage II, manufacturing enterprises mainly invest in technology management. By introducing technical management personnel and organizing employees to learn and train, the utilization rate of manufacturing technology and information technology in manufacturing enterprises is improved and technology integration and collaborative development are continuously improved. When the technology efficiency satisfies $|x - y| > \delta$, technology fusion will enter stage I or stage III. If $x - y > \delta$, technology fusion will enter stage III, otherwise stage I.

5.3 Robust analysis of stage III

Theorem 7 *When an enterprise is developing manufacturing technology, if the manufacturing technology efficiency development potential coefficient satisfies: $-\frac{\gamma_2\alpha_1}{\beta_1} < \alpha_2 < 2 - \frac{\gamma_2\alpha_1}{\beta_1}$, and $\beta_2 > \frac{\gamma_1\gamma_2}{\beta_1}$, $\frac{\alpha_2 + \frac{\gamma_2\alpha_1}{\beta_1}}{\left(\beta_2 - \frac{\gamma_1\gamma_2}{\beta_1}\right)} \geq y^*$, then the technology fusion system is robust in the development stage of manufacturing technology.*

Proof According to Eq. (8), let $y_{t+1} = \left(\alpha_2 + \frac{\gamma_2\alpha_1}{\beta_1} + 1\right)y_t + \left(\frac{\gamma_1\gamma_2}{\beta_1} - \beta_2\right)y_t^2$, we can obtain two fixed points of $y_{t+1} = f(y_t)$:

$$y_{t+1} = f(y_t) = \left(\alpha_2 + \frac{\gamma_2\alpha_1}{\beta_1} + 1\right)y_t + \left(\frac{\gamma_1\gamma_2}{\beta_1} - \beta_2\right)y_t^2.$$

According to the stability theorem, if y_1 is stable, it must satisfy

$$|f'(y)\|_{y_1} = \left|\alpha_2 + \frac{\gamma_2\alpha_1}{\beta_1} + 1\right| < 1.$$

If y_2 is stable, it must satisfy

$$|f'(y)\|_{y_2} = \left|\alpha_2 + \frac{\gamma_2\alpha_1}{\beta_1} + 1 + 2\left(\frac{\gamma_1\gamma_2}{\beta_1} - \beta_2\right)\frac{\alpha_2 + \frac{\gamma_2\alpha_1}{\beta_1}}{\beta_2 - \frac{\gamma_1\gamma_2}{\beta_1}}\right| < 1.$$

Therefore, according to the analysis, let $\begin{cases} |f'(y)\|_{y1} \geq 1 \\ |f'(y)\|_{y_2} < 1 \end{cases}$, we can obtain stable condition of y_2:

$$\begin{cases} \left|\alpha_2 + \frac{\gamma_2\alpha_1}{\beta_1} + 1\right| \geq 1 \\ \left|1 - \alpha_2 - \frac{\gamma_2\alpha_1}{\beta_1}\right| < 1 \end{cases}$$

In other words, when $-\frac{\gamma_2\alpha_1}{\beta_1} < \alpha_2 < 2 - \frac{\gamma_2\alpha_1}{\beta_1}$ and $\beta_2 > \frac{\gamma_1\gamma_2}{\beta_1}$,$y_1$ is unstable and y_2 stable. If $y_2 \geq y^*$, according to the definition of robustness in this paper, the technology fusion system is robustness when $-\frac{\gamma_2\alpha_1}{\beta_1} < \alpha_2 < 2 - \frac{\gamma_2\alpha_1}{\beta_1}$ and $\beta_2 > \frac{\gamma_1\gamma_2}{\beta_1}$.

Theorem 8 *When an enterprise is developing manufacturing technology, if the manufacturing technology convergence parameter satisfies* $\gamma_2 < \frac{\beta_1\beta_2}{\gamma_1}$, *by increasing the initial degree of manufacturing technology integration and collaborative development, the enterprise can effectively improve manufacturing technology efficiency in the development of manufacturing technology and can reduce the investment cost of enterprises.*

Proof : In the development stage of manufacturing technology, enterprises can effectively change the production frontier of manufacturing technology. As a result, the changes of production frontiers lead to changes of the manufacturing technology efficiency development potential coefficient α_2. According to Theorem 7, when the manufacturing technology efficiency development potential coefficient satisfies $-\frac{\gamma_2\alpha_1}{\beta_1} < \alpha_2 < 2 - \frac{\gamma_2\alpha_1}{\beta_1}$, the technology fusion system is in a robust state and the manufacturing technology efficiency is stable at $y = \frac{\alpha_2 + \frac{\gamma_2\alpha_1}{\beta_1}}{\beta_2 - \frac{\gamma_1\gamma_2}{\beta_1}}$. By stage II, we obtain $\gamma_1 > 0$. So $\gamma_2 < \frac{\beta_1\beta_2}{\gamma_1}$, if γ_2 becomes bigger, $\alpha_2 + \frac{\gamma_2\alpha_1}{\beta_1}$ will become bigger and $\beta_2 - \frac{\gamma_1\gamma_2}{\beta_1}$ will become smaller, thus $y = \frac{\alpha_2 + \frac{\gamma_2\alpha_1}{\beta_1}}{\beta_2 - \frac{\gamma_1\gamma_2}{\beta_1}}$ will become bigger. In addition, because γ_2 becomes bigger,$2 - \frac{\gamma_2\alpha_1}{\beta_1}$ will decrease. Therefore, the change of the production frontier of the enterprise will be reduced compared with the original, that is, the investment of the enterprise will be reduced. Theorem 8 is verified.

Through the investment of manufacturing technology, enterprises change the production frontier of manufacturing technology. As a result, the manufacturing technology development efficiency potential coefficient a_2 also changes. Stable promotion of technology fusion is very important for manufacturing enterprises, so enterprises should make manufacturing technology efficiency development potential coefficient change within a robust range $(-\frac{\gamma_2\alpha_1}{\beta_1}, 2 - \frac{\gamma_2\alpha_1}{\beta_1})$. However, when $x_{30} - \frac{2}{\beta_2 - \frac{\gamma_1\gamma_2}{\beta_1}} > \delta$, it means that if the manufacturing technology efficiency development potential coefficient a_2 changes in a robust interval, the technology fusion cannot enter stage II. Therefore, enterprises need to jump out of the current robust range of manufacturing technology efficiency development potential coefficient. At this time, when $\alpha_2 \geq 2 - \frac{\gamma_2 \alpha_1}{\beta_1}$, y_2 is no longer stable. When the value of α_2 deviates slightly from $2 - \frac{\gamma_2 \alpha_1}{\beta_1}$, $\{y_t\}$ no longer converges to y_2, and two subsequences y_1^*, y_2^* will appear and satisfy $y_{2t} \to y_1^*, y_{2t+1} \to y_2^*(t \to \infty)$. That is, small changes of α_2 will lead to the development of manufacturing technology efficiency into two different development paths. Currently, the robustness of the technology fusion system in the development stage of manufacturing technology decreases. And as α_2 continues to change, there may be a 4 times period bifurcation. In other words, if α_2 changes a little at the 4 times period bifurcation point that will make the development of manufacturing technology efficiency appear 4 development paths, which makes the manufacturing technology efficiency robust be lower than 2 times period. So with the increasing of α_2, the period-doubling bifurcation will affect the robustness of the technology fusion system in the manufacturing technology development stage. Therefore, in the development of manufacturing technology, it is very important for the robust operation of manufacturing enterprises to master the period-doubling bifurcation point of the evolution of manufacturing technology efficiency. The following gives the algorithm for finding the period-doubling bifurcation points and the robust theorem of period-doubling evolution.

Theorem 9 *In the development stage of manufacturing technology, if the values* $y_1^*, y_2^*, \ldots y_{2^i}^*$ *are stable fixed points of manufacturing technology efficiency within* 2^i *times period and satisfy* $y_i^* \geq y^*$ $(i = 1, 2, \ldots 2^i)$, *then the technology fusion system is weak robustness when* $c_{i-1} \leq \alpha_2 \leq c_i$, *where* c_{i-1} *is* 2^i *times period bifurcation point;* c_i *is* 2^i *times period bifurcation point*.

Theorem 10 *In the development stage of manufacturing technology, assuming the values* $y_1^*, y_2^*, \ldots y_{2^i}^*$ *are stable fixed points of manufacturing technology efficiency within* 2^i *times period, if there is* $y_i^* \in \{y_1^*, y_2^*, \ldots y_{2^i}^*\}$ *and satisfies* $y_i^* < y^*(i \in \{1, 2, \ldots 2^i\})$, *then the technology fusion system is not robust when* $c_{i-1} \leq \alpha_2 \leq c_i$. *According to self-similarity, if* $\alpha_2 > c_i$, *technology fusion is also not robust.*

The following gives an algorithm for solving the period-doubling bifurcation point and judging the period-doubling evolution of manufacturing technology efficiency according to Theorems 9 and 10.

Algorithm2: Establishment of Robust Evolutionary Dynamic Model for SMISs

Input: The system parameter values $\alpha_1, \alpha_2, \beta_1, \beta_2, \gamma_1, \gamma_2$.

the minimum requirements of enterprises for information technology y_{20}.

Output: Robustness of dynamics model and bifurcation point of value α_2.

1: **Begin {**

2: $p = \dfrac{\gamma_2 \alpha_1}{\beta_1} + 1$; $q = \dfrac{\gamma_1 \gamma_2}{\beta_1} - \beta_2$.

3: $f(x) = (\alpha_2 + p)x + qx^2$.

4: **for** i=1 to N, where N is a given constant, $N = 5$ given in this paper. Generally speaking, $N > 5$ chaos appears.

5: $F(y) = f^{(2^i)}(y)$, where $f^{(2^i)}(y)$ represents 2^i compound operations on $f(y)$: $f^{(2^i)} = \underbrace{f(f(f(\cdots f(y))))}_{2^i}$.

6: $X_i = solve(F(y) = 0)$, where $X_i = \{y_1, y_2, \cdots y_{2^{2^i}}\}$ represents the set of solutions.

7: $Y_i = \{X_i^1, X_i^2, \cdots X_i^{C_{2^{2^i}}^{2^i}}\}$,where $X_i^j (j = 1,2 \cdots C_{2^{2^i}}^{2^i})$ represents the jth subset composed of 2^i solutions selected from the solution set $X_i = \{y_1, y_2, \cdots y_{2^{2^i}}\}$.

8: **for** j=1 to $C_{2^{2^i}}^{2^i}$

9: **if** $|F^{'}(y)| < 1$ for any $y \in X_i^j$ and $|F^{'}(y)| \geq 1$ for any $y \in X_i^j / X_i^j$

10: $y \in X_i^j$ represents the set of all stable fixed points of the dynamic system, and get the 2^i times period bifurcation point b_i in dynamic system.

11: **if** $y \geq y^*$ for any $y \in X_i^j$

12: The dynamic system is weak robustness in the interval $c_{i-1} < \alpha_2 < c_i$,where c_{i-1} is 2^{i-1} times period bifurcation point.

13： **else** The dynamic system is not robustness in the interval $c_{i-1} < \alpha_2 < c_i$

14： **end**

15： **else** continue

16: **end**

17: **end**

18: **end**

19: **return** The robustness of dynamic system and 2^i times period bifurcation point c_i

20： } **end**

6 Case study

As mentioned above, the technology fusion of manufacturing enterprises follows three stages. Stage I is that manufacturing technology is ahead of information technology. Enterprises are committed to the development of information technology. Stage II is that manufacturing technology and information technology are at a flat state. Enterprises invest in technology management to improve technology integration and collaborative development. In stage III, manufacturing technology lags information technology and enterprises are committed to the development of manufacturing technology. Since then, the three phases have cycled with each other.

This paper selects a small- and medium-sized tool manufacturing company "Yonggu Group" located in Wenzhou, China, for case analysis. During the 7 years from 2013 to 2020, due to financial constraints, the enterprise did not carry out technology introduction but based on the enterprise's existing information technology and manufacturing technology, through technology integration and collaborative development to continuously promote technology fusion. Since there is no introduction of new technology, the enterprise's information technology efficiency development potential coefficient and manufacturing technology development potential coefficient have not changed. Its development potential coefficient and damping coefficient are

$$\alpha_1 = 1.85, \alpha_2 = 1.8, \beta_1 = 3.3, \beta_2 = 3.6.$$

Through the introduction of relevant talents in the past 7 years, the enterprise's technology integration and collaborative development have been significantly improved:

$$\begin{aligned} &2013{-}2018: \quad \gamma_1 = -0.4, \gamma_2 = -0.5 \\ &2018{-}2020: \quad \gamma_1 = 0.25, \gamma_2 = 0.15 \end{aligned}$$

Notation The above data are shown in the attached data.

Now we simulate the evolution of the information technology production frontier, based on the theory proposed in this paper.

6.1 Stage I

We verify the influence of information technology efficiency development potential coefficient on the robustness of technology fusion. In the development stage of information technology, firstly we analyze the evolutionary trajectories when manufacturing technology and information technology are not completely integrated. In stage I, by calculating the initial manufacturing technology efficiency of the enterprise, we can obtain $y_{10} = 0.48$ and the initial information technology efficiency is 0.1. The parameters of the technology fusion system are as follows

$$\begin{aligned} \alpha_1 &= 0 : 0.001 : 2.87, \alpha_2 = 1.8, \beta_1 = 3.3, \beta_2 \\ &= 3.6, \gamma_1 = -0.4, \gamma_2 = -0.5, x(0) = 0.1 \end{aligned}$$

Figure 5 shows that the robustness of technology efficiency development potential coefficient varies by α_1. From Fig. 5, when $0 \leq a_1 \leq 0.3$, $x = 0$. In this scenario, the main roles of information technology in manufacturing enterprises are human resource management, ordering, piece counting, etc. Information technology is rarely used effectively in manufacturing enterprises, so it does not bring actual benefits to the manufacturing enterprise. When $0.3 \leq a_1 \leq 1.79$, through investment in information technology, the manufacturing enterprise introduces new information technology to improve the informatization of enterprises and increases the enterprise's profits, so that information technology brings benefits to manufacturing enterprises. However, the actual information technology efficiency does not satisfy the expected value $x^* = 0.46$ of the manufacturing enterprise. According to Theorem 1, the technology fusion is in a not robust state currently. When $1.79 \leq a_1 < 2.26$ the actual information technology efficiency of the manufacturing enterprise is higher than the expected value $x^* = 0.46$ of the enterprise and the evolution path of information technology efficiency is stable at $x = 0.61$. Therefore, according to Theorem 1, the technology fusion in the manufacturing enterprise is in a robust state. According to Algorithm 1, $a_1 = 2.26$ is the 2 times period bifurcation point of the information technology efficiency evolutionary, which means that a small change of a_1 around $a_1 = 2.26$ may lead to two evolutionary paths in the development of information technology efficiency. Therefore, when $2.26 \leq a_1 < 2.74$, each parameter a_1 of the technology fusion system corresponds to two possible evolutionary paths, and each path is stable and the information technology efficiency is greater than the expected value of the manufacturing enterprise. So according to Theorem 3, the evolution of the technology fusion system is weakly robust in the information technology development stage and the maximum technical efficiency is 0.88 when $a_1 = 2.74$. According to Algorithm 1, $a_1 = 2.74$ is the 4 times period bifurcation point of the information technology efficiency evolutionary, which means that a small change of a_1 around $a_1 = 2.74$ may lead to four evolutionary paths in the development of information technology efficiency. Therefore, when $2.74 \le a_1 < 2.78$, each parameter a_1 of the technology fusion system corresponds to four possible evolutionary paths and each path is stable. However, there is one evolutionary path that information technology efficiency does not satisfy the expected value of the manufacturing enterprise, so according to Theorem 4, the evolution of technology fusion system is not robust in the information technology development stage. In the same way, according to Algorithm 1, when $a_1 = 2.78$, the evolution of information technology efficiency appears chaos. For the technology fusion, chaos refers to the development of enterprise technology fusion into unhealthy operation. At this time, the relationship between information technology efficiency and a_1 is intricate and the information technology efficiency evolution falls into chaos. Through the above analysis, we find that when $\alpha_1 = 1.85$, the technology fusion of the enterprise is in a robust state. Because the current production frontier of the enterprise satisfies the development needs of the enterprise, the enterprise has not introduced new information technology.

Through the analysis of Fig. 6, we can see that the information technology efficiency evolution system will fall into chaos when $\alpha_1 = 2.78$ verifying the analysis of Fig. 5.

In Fig. 7, we compare the actual dynamic evolution process of enterprise information technology efficiency ($\alpha_1 = 1.85$) with the dynamic evolution process under the weakly robust state ($\alpha_1 = 2.5$) and the dynamic evolution process under the chaotic state ($\alpha_1 = 2.85$). Through Fig. 7, we can see that the evolution of information technology efficiency in the chaotic state is irregular, the evolution of information technology in the weakly robust state is periodic, and the evolution of information technology efficiency in the robust state is stable.

In addition, we can see that in the chaotic state, the maximum information technology efficiency is greater than the maximum information technology efficiency of the weakly robust state, and the maximum information technology efficiency of the weakly robust state is greater than that of the robust state. This is obviously in line with the law of economic development, and high risk means high income. Therefore, in the development stage of information technology, the development of information technology from the early stage to the mature stage should be in a robust or weakly robust state according to the needs of the enterprise.

Next, to verify Theorem 2, we discuss the impact of the current enterprise technology integration and collaborative development on the evolution of

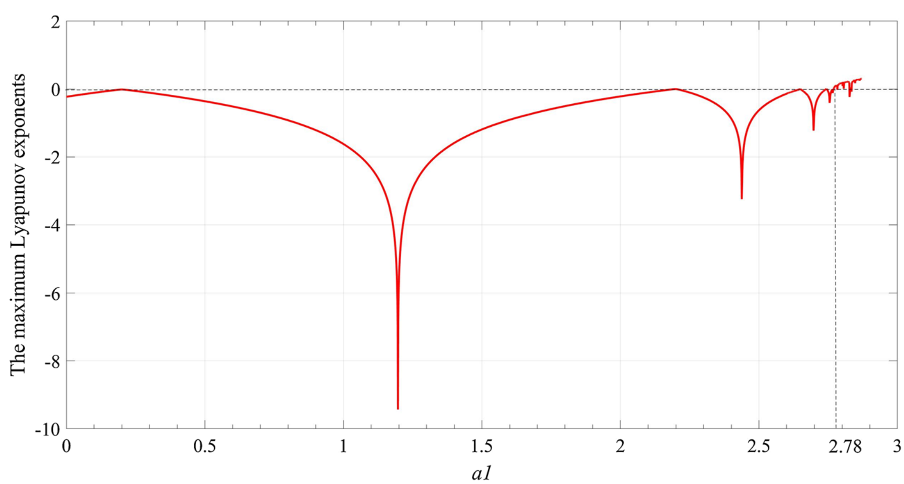


Fig. 6 The maximum Lyapunov exponent ($\gamma_1 = -0.4, \gamma_2 = -0.5$)

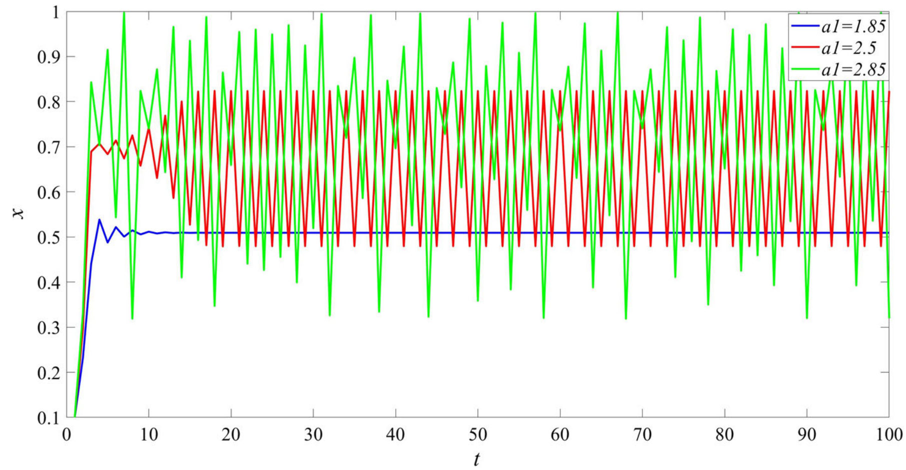


Fig. 7 Information technology efficiency dynamic evolution ($\alpha_1 = 1.85, \alpha_1 = 2.5, \alpha_1 = 2.85$)

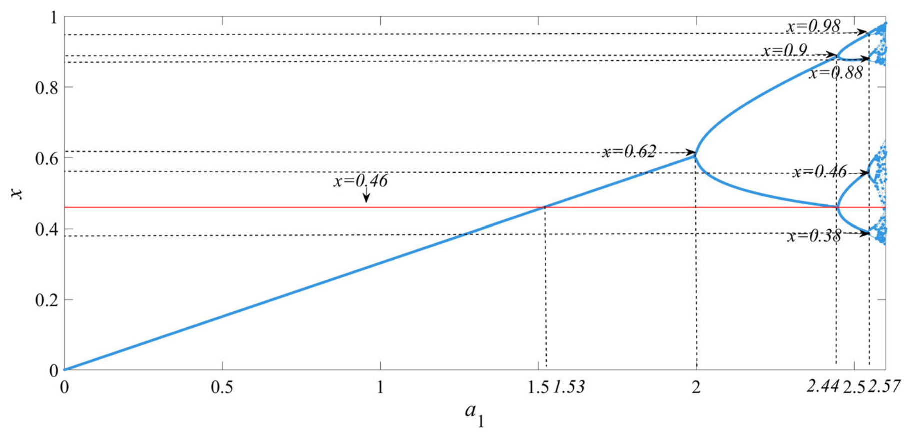


Fig. 8 Information technology efficiency evolution analysis ($\gamma_1 = 0, \gamma_2 = 0$)

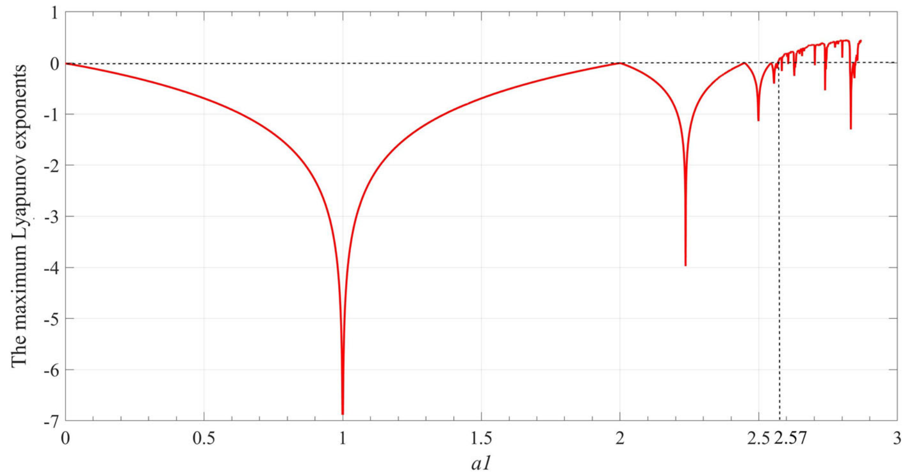
technology fusion during the development stage of information technology. We mainly discuss complete integration and complete not integration. First, when manufacturing technology and information technology are complete integration:

$$\alpha_1 = 0 : 0.001 : 2.63, \alpha_2 = 1.8, \beta_1 = 3.3, \beta_2 = 3.6, \gamma_1 = 0, \gamma_2 = 0, x(0) = 0.1$$

Compared with Fig. 5, when manufacturing technology and information technology are complete integration, there is no situation where the information technology efficiency is 0. Because the information technology and manufacturing technology at this time are matched, and information technology helps enterprises to improve the productivity of enterprises. In Fig. 8, when information technology and manufacturing technology are complete integration, according to Theorem 1 and Algorithm 1, in the development stage of information technology, technology fusion system is robust when $\alpha_1 \in [1.53, 2)$, and when $\alpha_1 = 2$, the maximum of information technology efficiency is 0.62. The technology fusion system is weak robust when $\alpha_1 \in [2, 2.44)$, and when $\alpha_1 = 2.44$, the maximum of information technology efficiency is 0.9. Compared with Fig. 5, the integration of information technology and manufacturing technology helps enterprises improve technology efficiency and achieve robustness earlier. In other words, achieving robustness earlier can help enterprises reduce the investment of manufacturing enterprises. Theorem 2 is verified.

Through the analysis of Fig. 9, we can see that the information technology efficiency development system will fall into chaos when $\alpha_1 = 2.57$, verifying the analysis of Fig. 8. Comparing Fig. 6, we can conclude

Fig. 9 The maximum Lyapunov exponent ($\gamma_1 = 0, \gamma_2 = 0$)



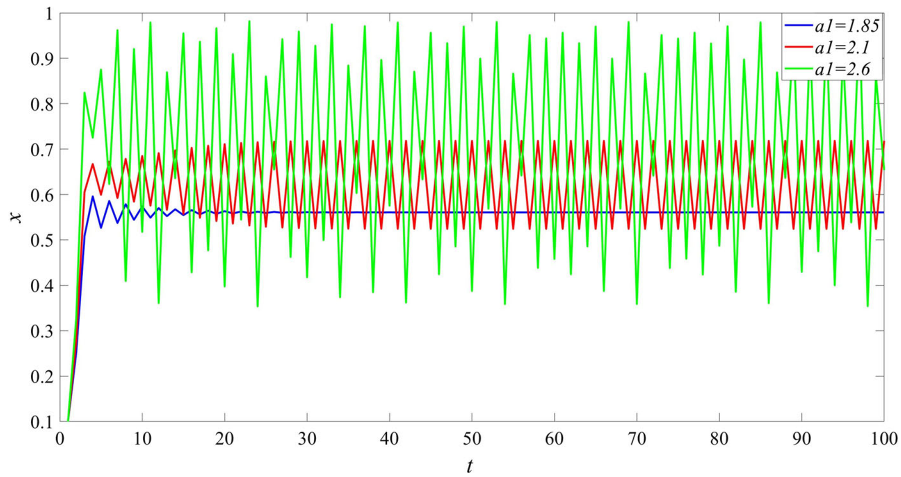


Fig. 10 Information technology efficiency dynamic evolution ($\alpha_1 = 1.85, \alpha_1 = 2.1, \alpha_1 = 2.6$)

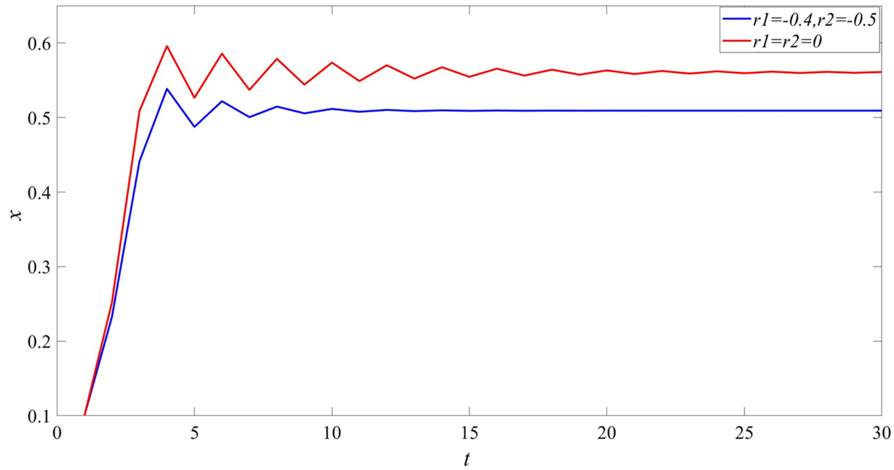
that the difference in the state of technological fusion will affect the magnitude of the driving force when the development of enterprise information technology enters a state of chaos.

In Fig. 10, we can see that the robust state, weakly robust state, and chaotic state of the information technology efficiency evolution are very similar to Fig. 7. In other words, the three dynamic evolution laws of the information technology development have self-similarity among different fusion degrees γ_1, γ_2.

In Fig. 11, we found that the degree of technological fusion γ_1, γ_2 will affect the final stable value and stable time of information technology efficiency when other parameters remain unchanged. The greater the degree of technological fusion, the higher the final information technology efficiency, and the longer the fluctuation time of the information technology efficiency in the evolution process.

Through the above case analysis, we can see that when information technology converges to manufacturing technology, the dissipating force $\left(\beta_1 - \frac{\gamma_1\gamma_2}{\beta_2}\right)x^2(t)$ of information technology development can be reduced by improving the fusion of technology; at the same time, driving force $\left(\alpha_1 + \frac{\gamma_1\alpha_2}{\beta_2} + 1\right)x(t)$ of information technology development can be improved. This makes the gap between the driving force and the dissipating force of information technology development smaller. Therefore, when enterprises increase the Information Technology

Fig. 11 The influence of technology integration state on the development of information technology



Efficiency Development Potential Coefficient through investment, it is easier to make the driving force and dissipating force of the information technology development reach the same state, making it easier for the enterprises to fall into chaos, as shown in Figs. 6 and 9. In addition, due to the increase in technology fusion, the dissipating factor $\left(\beta_1 - \frac{\gamma_1\gamma_2}{\beta_2}\right)$ becomes smaller, while the driving coefficient $\left(\alpha_1 + \frac{\gamma_1\alpha_2}{\beta_2} + 1\right)$ becomes larger. Therefore, the steady state of information technology development $x(t) = \frac{\alpha_1 + \frac{\gamma_1\alpha_2}{\beta_2}}{\beta_1 - \frac{\gamma_1\gamma_2}{\beta_2}}$ becomes larger with the increase in technology fusion, as shown in Fig. 11. When the development of information technology has entered a mature period, the investment of enterprises in information technology will make the driving force and dissipating force of information technology development fiercely competitive, causing fluctuations and even chaos for enterprises in the development of information technology, as shown in Figs. 7 and 10. Therefore, when enterprise technology fusion reaches the maturity state, the enterprise needs to start a new development stage through enterprise transformation.

6.2 Stage II

In stage I, the manufacturing enterprise increased the information technology efficiency $x = 0.51$ by investing in information technology, so that the information technology efficiency and manufacturing technology efficiency satisfy

$$|x - y_{10}| = |0.51 - 0.48|0.03 < \delta = 0.04.$$

So, the enterprise technology fusion entered stage II. In the stage II, the main purpose of the enterprise is to improve the technology management level of the enterprise so that the technical management level matches the technical level, thereby improving the integration and collaborative development of information technology and manufacturing technology.

First, through Fig. 5, we can see that the current production frontier satisfies the needs of enterprises. Therefore, we will promote enterprise technology integration and collaborative development by improving the enterprise management level. The technology fusion system parameters are as follows

$$\gamma_1 = 0 : 0.001 : 1, \gamma_2 = \gamma_1 - 0.1, \alpha_2 = 1.8, \alpha_1 = 1.85, \beta_1 = 3.3, \beta_2 = 3.6$$

$$x(0) = 0.51, y(0) = 0.48$$

On the basis of stage I, in stage II, the enterprise improves the existing technology management level to make the existing technology level satisfy the current technological needs and improve the technology integration and collaborative development of information technology and manufacturing technology. Next, through Fig. 12, we discuss the influence of the robustness of the technology fusion evolution process as the convergence parameters changes.

Through the first sub-figure of Fig. 12, we can know that when $\gamma_1 \in [-0.4, 0.25]$, the manufacturing enterprise's information technology efficiency does not reach the enterprise's expected value $x^* = 0.6$.

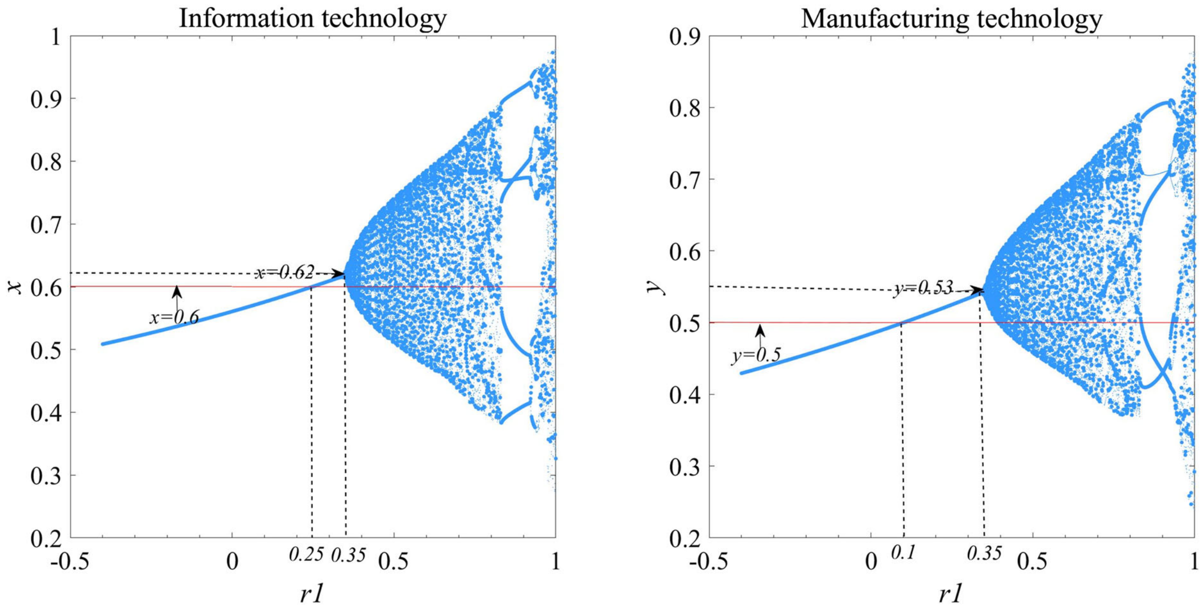


Fig. 12 Analysis of technology efficiency in the stage of technology efficiency integration and collaborative development ($\gamma_1 - \gamma_2 = 0.1$)

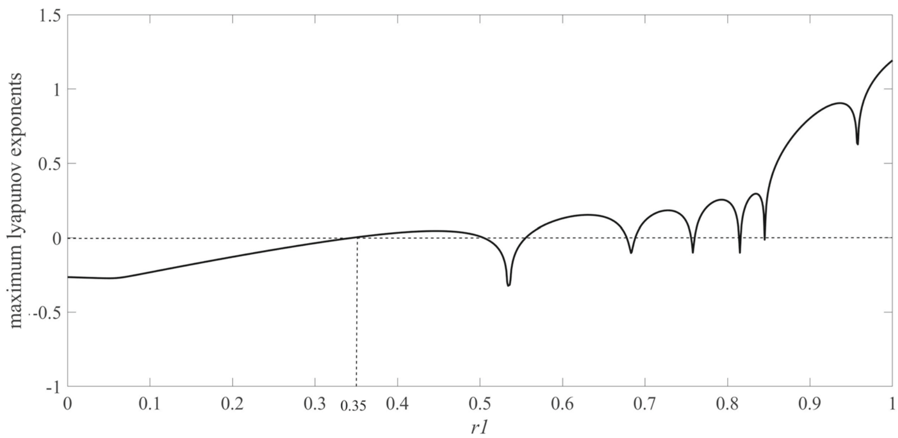
According to Theorem 5, the manufacturing enterprise's information technology is not robust at this stage. The reason is that although the manufacturing enterprise has improved its information technology through investment in the stage I, the existing information technology management level cannot apply information technology, so the enterprise needs to gradually improve the integration and collaborative development of technologies to improve the information technology efficiency. When the enterprise information technology convergence parameter reaches $\gamma_1 = 0.25$, the manufacturing enterprise's information technology efficiency will satisfy the needs of the enterprise, then the evolution of information technology from the not robust stage to the robust stage. Therefore, according to Theorem 5, when the information technology convergence parameter satisfies $0.25 \leq \gamma_1 < 0.35$, the evolution path of information technology efficiency is robust. Therefore, to improve the information technology efficiency of the enterprise, enterprises should improve the management level of information technology through reasonable investment to make information technology convergence parameter satisfy $0.25 \leq \gamma_1 < 0.35$. When $\gamma_1 > 0.35$, the evolution of information technology is in chaos. The reason for getting into chaos is that the level of information technology management does not match the information technology. Similar to the evolution of information technology efficiency, through the second sub-graph of Fig. 12, we can know that when $\gamma_2 \in [-0.5, 0)$, the manufacturing technology efficiency does not reach the expected value $y^* = 0.5$ of the enterprise, so according to Theorem 5, the evolution of the manufacturing technology efficiency at this stage is not robust. When the manufacturing technology convergence parameter reaches $\gamma_2 = 0$, the manufacturing technology efficiency will satisfy the exception $y^* = 0.5$ of the enterprise. At this time, the evolution of manufacturing technology efficiency will enter the robust stage from the not robust stage. According to Theorem 5, when the manufacturing technology convergence parameter satisfies $0 \leq \gamma_2 < 0.25$, the evolution path of manufacturing technology efficiency is robust. Therefore, to improve the manufacturing technology efficiency of the enterprise, enterprises should improve the management level of manufacturing technology through reasonable investment and make manufacturing technology convergence parameter satisfy $0 \leq \gamma_2 < 0.25$. When $\gamma_1 > 0.25$, the evolution of manufacturing technology is in chaos. The reason for getting into chaos is that the level of manufacturing technology management does not match the information technology.

Through the analysis of Fig. 13, we can see that the technology fusion system will fall into chaos when $\gamma_1 = 0.35$, verifying the analysis of Fig. 12.

Through Fig. 14, we can see that the actual dynamic evolution process of the enterprise technology fusion system is robust. However, as mentioned earlier in this paper, the purpose of the robust operation of the technology fusion or development is to prevent the enterprise's technology fusion or development from falling into chaos during each stage of technology fusion or development from the initial stage to the mature period. When the enterprise technology fusion of development reaches the mature stage, if the enterprise does not carry out the next stage of technological reform, then the technical efficiency will always remain in this state. The result is that the products produced by the enterprise are gradually eliminated by the market and the enterprise faces bankruptcy.

Through Fig. 15, we can see that if the technological fusion of the enterprise falls into chaos, the dynamic evolution of technical efficiency becomes irregular. The result is that the enterprise's resource allocation is unreasonable and the quality of the products produced is uneven, which is easy to make the enterprise face the risk of bankruptcy. So, for enterprises, the chaotic state and long-term stable state of the technology fusion system are very harmful to

Fig. 13 The maximum Lyapunov exponent $(\gamma_1 - \gamma_2 = 0.1)$



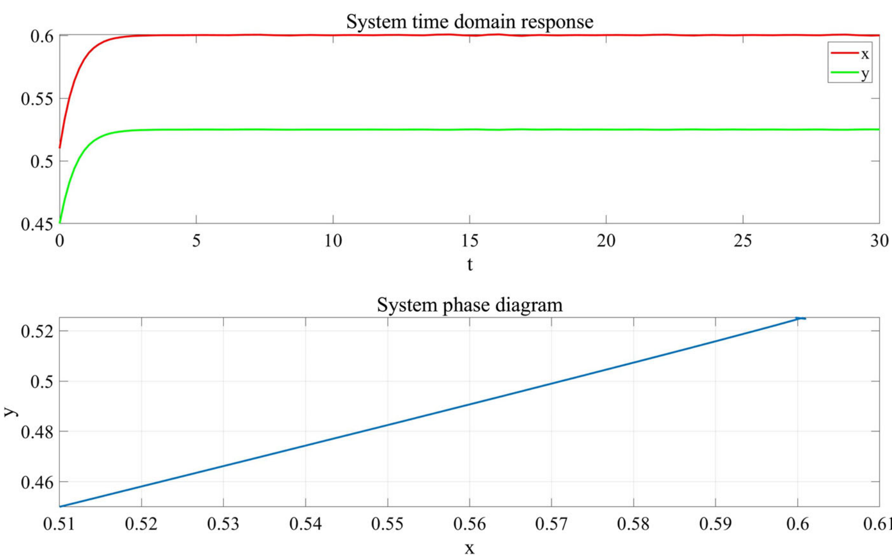


Fig. 14 Technology efficiency dynamic evolution $(\gamma_1 = 0.25, \gamma_2 = 0.15)$

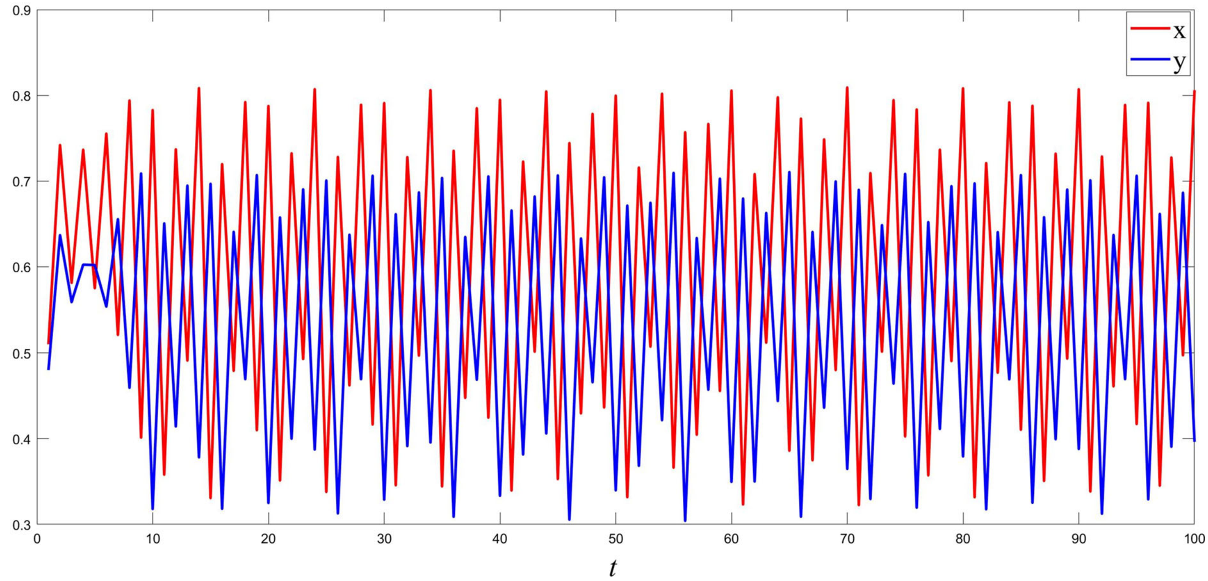


Fig. 15 Technology efficiency dynamic evolution ($\gamma_1 = 0.6, \gamma_2 = 0.5$)

the development of enterprises. Therefore, enterprises should choose a robust or weakly robust development state in the early stage of technological fusion to prevent falling into chaos. After the technology fusion is mature, carry out reforms and enter the manufacturing technology development stage or the information technology development stage to prevent enterprise products and technologies from being eliminated by the market.

Through the analysis of the above experiments, we find that under the current degree $\gamma_1 = 0.25, \gamma_1 = 0.15$ of collaborative development of technology, the process of enterprise technology fusion is robust. Now, to verify Theorem 6, we do the following simulation experiments:

$$\gamma_1 = 0 : 0.001 : 1, \gamma_2 = \gamma_1 - 0.2, \alpha_2 = 1.8, \alpha_1 = 1.85, \beta_1 = 3.3, \beta_2 = 3.6$$

$$x(0) = 0.51, y(0) = 0.48$$

Through Fig. 16, according to Theorem 5, we can know that the evolution of information technology efficiency is not robust at $\gamma_1 \in [0, 0.27)$, robust at $\gamma_1 \in [0.27, 0.42)$. When $\gamma_1 = 0.42, x = 0.63$. Similarly, the evolution of manufacturing technology efficiency is not robust at $\gamma_2 \in [-0.2, 0.03)$, robust at $\gamma_2 \in [0.03, 0.22)$, when $\gamma_2 = 0.22, y = 0.54$. Compared with Fig. 12, we can know that increasing the gap Δ between the information technology convergence parameter and manufacturing technology convergence parameter will promote the improvement of technology efficiency. Theorem 6 is verified.

Through the analysis of Fig. 17, we can see that the technology fusion system will fall into chaos when $\gamma_1 = 0.42$, verifying the analysis of Fig. 16. Comparing Fig. 13, we can conclude that the difference between the degree of fusion of manufacturing technology and the degree of fusion of information technology will affect the value γ_1 when the enterprise technology fusion system enters a state of chaos.

By comparing Figs. 14 and 18, we found that the gap between the degree of fusion of manufacturing technology and the degree of fusion of information technology will affect the final stable value of the manufacturing technology efficiency, and the final value of information technology efficiency will not have a big impact.

Different from the stage I and stage III of technology fusion, in the initial period of stage II of technology fusion, manufacturing technology and information technology are in a state of coordinated development. However, due to the limited resources of enterprises and the difference in resource requirements for technology development in different fields, manufacturing technology and information technology cannot always maintain a coordinated development state. Therefore, with the difference in resource

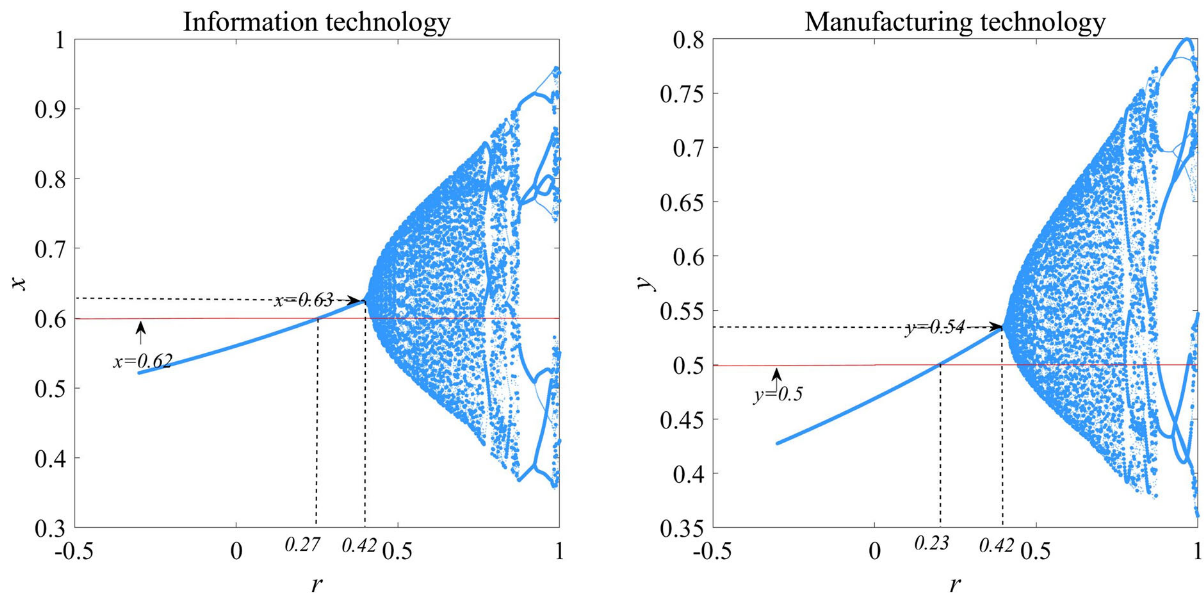


Fig. 16 Analysis of technology efficiency in the stage of technology efficiency integration and collaborative development ($\gamma_1 - \gamma_2 = 0.2$)

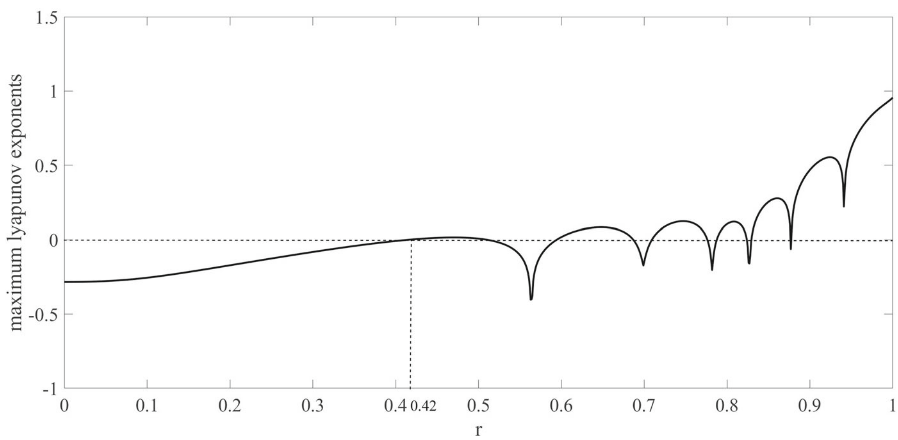


Fig. 17 The maximum Lyapunov exponent ($\gamma_1 - \gamma_2 = 0.2$)

input, there is a gap between γ_1 and γ_2. Due to the gap between γ_1 and γ_2, manufacturing technology and information technology gradually become incompatible after the maturity of stage II, which in turn will make the development of technology fusion enter stage I or stage III. In addition, the increase in the gap between γ_1 and γ_2 makes the dissipating force of technology fusion development larger, and thus the driving force required when technology fusion falls into chaos becomes larger, as shown in Figs. 13 and 17.

6.3 Stage III

In stage II, $x = 0.62, y = 0.52$, the information technology efficiency at this time is greater than the manufacturing technology efficiency and satisfies $x - y = 0.08 > \delta = 0.04$, so the technology fusion of the enterprise can enter stage III. In stage III, we discuss the robust evolution of manufacturing technology development when we change the manufacturing technology efficiency potential coefficient through changing the manufacturing technology production frontier. The system parameters are as follows

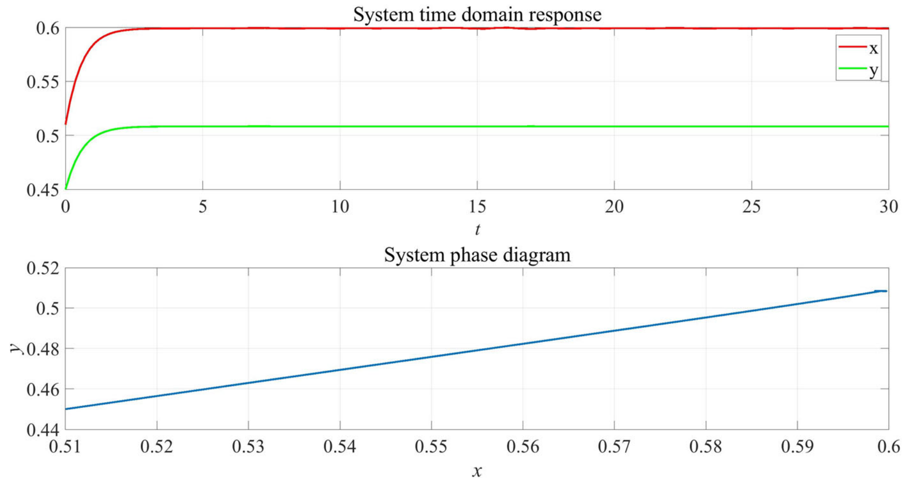


Fig. 18 Technology efficiency dynamic evolution ($\gamma_1 - \gamma_2 = 0.2$)

$$\alpha_2 = 0 : 0.001 : 2.7, \alpha_1 = 1.85, \beta_1 = 3.3, \beta_2 = 3.6, \gamma_1 = 0.25, \gamma_2 = 0.15$$

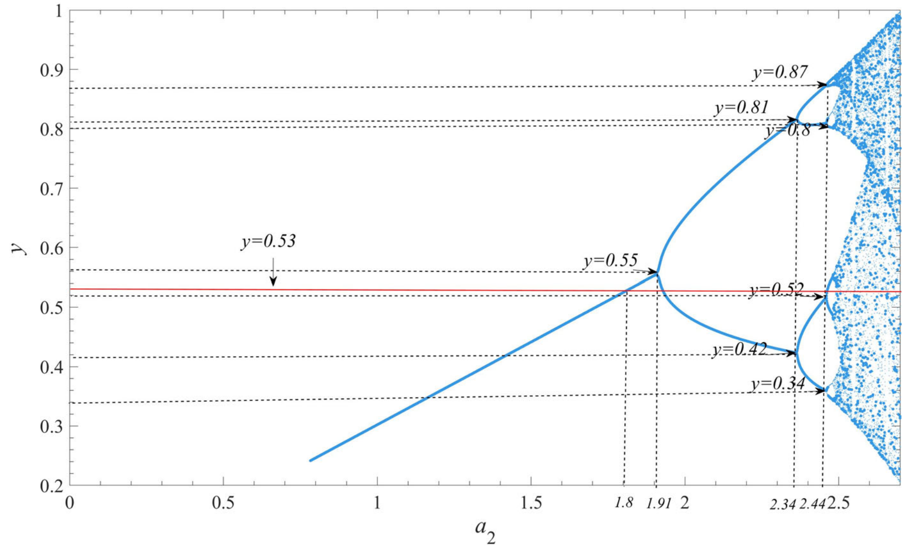
$$y(0) = 0.52, x_{30} = 0.62$$

The manufacturing enterprise introduces new manufacturing technologies through investment to change the development potential coefficient of manufacturing technology. Through Fig. 9, we can know that when the manufacturing technology efficiency development potential coefficient $\alpha_2 \in [0.75, 1.8)$, the manufacturing technology efficiency does not get the enterprise's expected value $y^* = 0.53$, so according to Theorem 7, the technology fusion system is in a not robust state in the stage of manufacturing technology development. When $\alpha_2 \in [1.8, 1.91)$, the manufacturing technology efficiency of the enterprise satisfies the requirements of the enterprise, and the evolution of manufacturing technology efficiency has only a stable trajectory. Therefore, according to Theorem 7, the technology fusion of the enterprise is in a robust state at this time and $y = 0.55$ when $\alpha_2 = 1.91$. According to Algorithm 2, $\alpha_2 = 1.91$ is the 2 times period bifurcation point of the manufacturing technology efficiency evolutionary, which means that a small change of α_2 around $\alpha_2 = 1.91$ may lead to two evolutionary paths in the development of manufacturing technology efficiency. Therefore, when $\alpha_2 \in [1.91, 2.34)$, each parameter α_2 of the technology fusion system corresponds to two possible evolutionary paths, and there is one evolutionary path not satisfying the expected value of the manufacturing enterprise, so according to Theorem 10, the evolution of the technology fusion system is not robust in manufacturing technology development stage. And according to the self-similar principle of Theorem 10, when $\alpha_2 > 1.91$, the evolution of the technology fusion system is not robust in the manufacturing technology development stage. In addition, when $\alpha_2 = 2.44$, the enterprise technology fusion will fall into chaos. Through analysis, when $\alpha_2 = 1.8$, enterprise technology fusion system is in a robust state and satisfies the exception of enterprise development, so "Yonggu Group" does not need to spend a lot of money to introduce new manufacturing technology at this time (Fig. 19).

Through the analysis of Fig. 20, we can see that the manufacturing technology development system will fall into chaos when $\alpha_2 = 2.44$, verifying the analysis of Fig. 19.

In Fig. 21, we compare the actual dynamic evolution process of enterprise manufacturing technology efficiency $(\alpha_2 = 1.8)$ with the dynamic evolution process under the weakly robust state $(\alpha_2 = 1.92)$ and the dynamic evolution process under the chaotic state $(\alpha_2 = 2.5)$. Through Fig. 21, we can see that the evolution process of manufacturing technology efficiency in the chaotic state is irregular, the evolution process of manufacturing technology in the weakly robust state is periodic, and the evolution of manufacturing technology efficiency in the robust state is stable. In addition, we can see that in the chaotic state, the maximum manufacturing technical efficiency is greater than the maximum manufacturing technical efficiency in the weakly robust state, and the maximum manufacturing technical efficiency in the weakly

Fig. 19 Manufacturing technology efficiency evolution analysis ($\gamma_1 = 0.25, \gamma_2 = 0.15$)



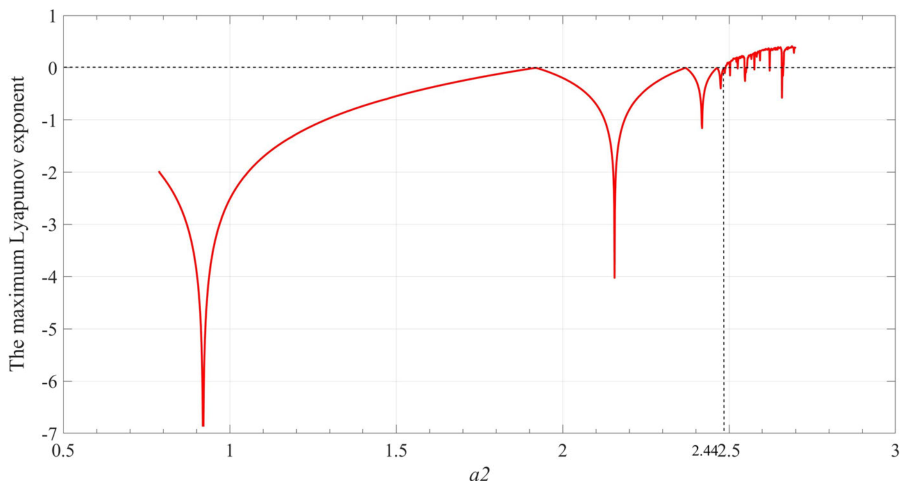


Fig. 20 The maximum Lyapunov exponent ($\gamma_1 = 0.25, \gamma_2 = 0.15$)

robust state is greater than the manufacturing technical efficiency in the robust state. Therefore, according to the needs of the development of manufacturing technology, enterprises should make their manufacturing technology enter the mature period from the early state in a robust or weakly robust state. After the mature stage, the enterprise should go from the manufacturing technology development stage to the technological fusion development stage.

Next, to verify Theorem 8, we do the following simulation. The coefficients are as follows

$$\alpha_2 = 0 : 0.001 : 2.67, \alpha_1 = 1.85, \beta_1 = 3.3, \beta_2 = 3.6, \gamma_1 = 0.5, \gamma_2 = 0.3$$

$$y(0) = 0.52$$

In Fig. 19, we can know that the robust interval of the evolution of manufacturing technology efficiency is $\alpha_2 \in [1.8, 1.91]$, and when $\alpha_2 = 1.91, y = 0.55$. In Fig. 10, we can know that the robust interval of the evolution of manufacturing technology efficiency is $\alpha_2 \in [1.7, 1.83]$, and when $\alpha_2 = 1.83, y = 0.56$. Because $\gamma_2 = 0.3 < \frac{\beta_1 \beta_2}{\gamma_1} = 23.76$, by comparing Figs. 19 and 22, we can know that the increase of

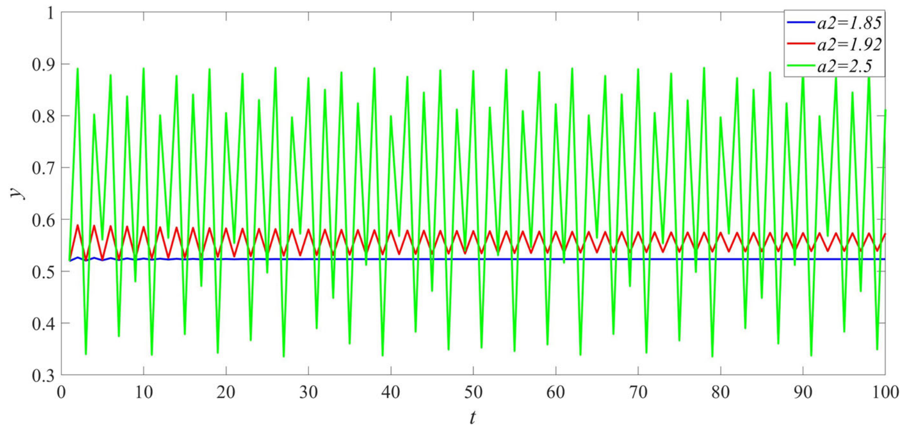
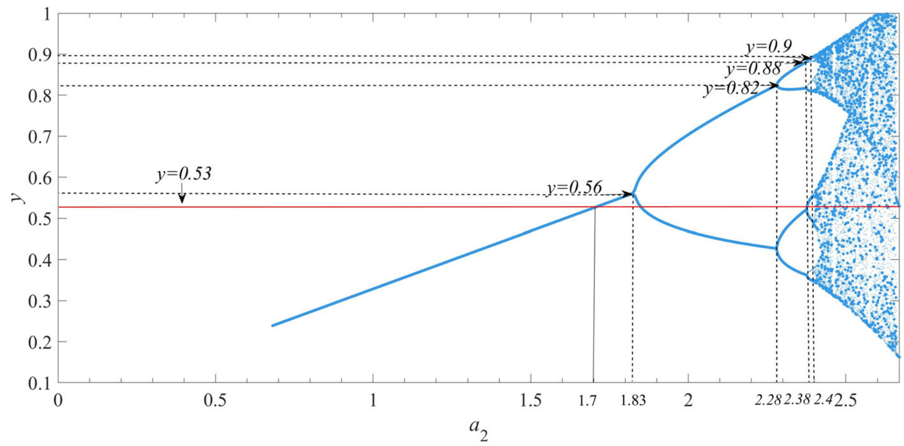


Fig. 21 Manufacturing technology efficiency dynamic evolution $(\alpha_2 = 1.8, \alpha_2 = 1.92, \alpha_2 = 2.5)$

Fig. 22 Manufacturing technology efficiency evolution analysis $(\gamma_1 = 0.5, \gamma_2 = 0.3)$



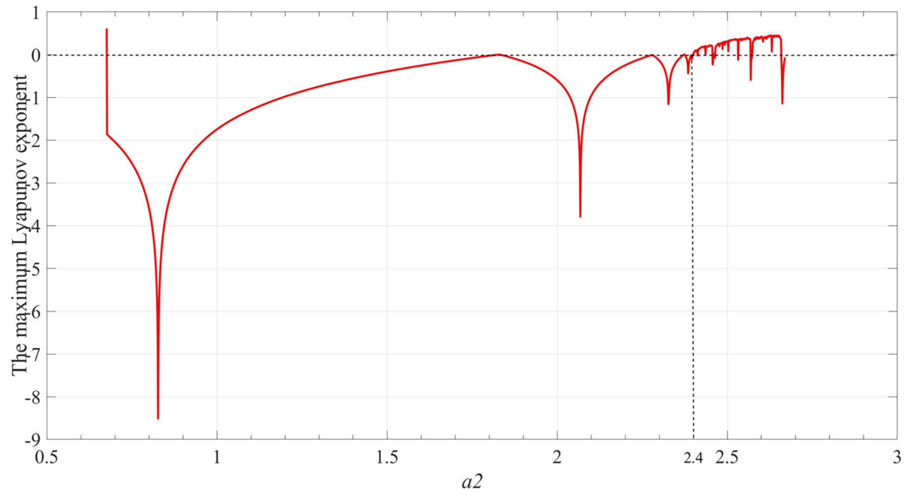
the collaborative development of manufacturing technology can not only improve the manufacturing technology efficiency, but also make the manufacturing technology development potential coefficient be smaller. This means that the increase in the degree of collaborative development of manufacturing technology can not only help the enterprise improve the manufacturing technology efficiency, but also help the enterprise reduce investment. Therefore, Theorem 8 is verified. Therefore, before developing manufacturing technology, the enterprise can promote the increase in the integration and collaborative development of manufacturing technology and information technology by improving the level of technology management that can help the enterprise achieve higher manufacturing technology efficiency.

Through the analysis of Fig. 23, we can see that the manufacturing technology development system will fall into chaos when $\alpha_2 = 2.4$, verifying the analysis of Fig. 22. Comparing Fig. 20, we can conclude that the difference in the state of technological fusion will affect the driving force when the development of enterprise manufacturing technology enters a state of chaos.

In Fig. 24, we can see that the robust state, weakly robust state, and chaotic state of the manufacturing technology efficiency evolution are very similar to Fig. 21, which means that the three dynamic evolution laws of the manufacturing technology development system have self-similarity among different fusion degrees γ_1, γ_2.

In Fig. 25, we found that the degree of technological fusion will affect the final stable value and stable time of manufacturing technology efficiency when other parameters remain unchanged. Generally speaking, the greater the degree of technological

Fig. 23 The maximum Lyapunov exponent ($\gamma_1 = 0.5, \gamma_2 = 0.3$)



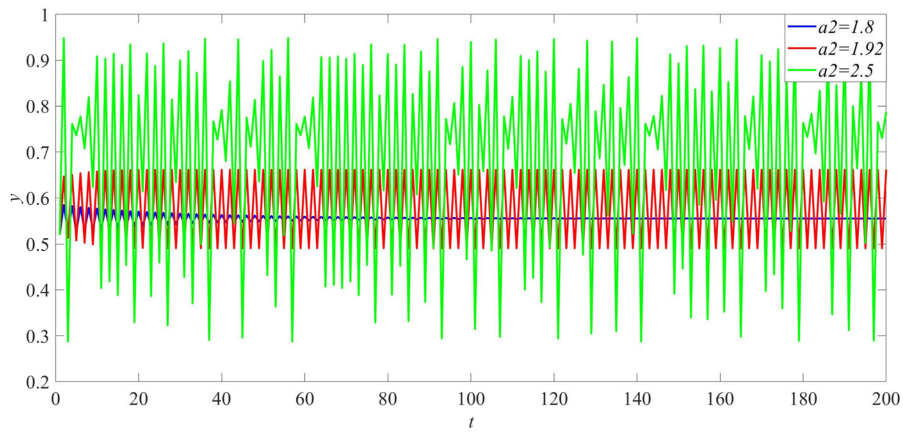


Fig. 24 Manufacturing technology efficiency dynamic evolution ($\alpha_2 = 1.8, \alpha_1 = 1.92, \alpha_1 = 2.5, \gamma_1 = 0.5, \gamma_2 = 0.3$)

fusion γ_1, γ_2, the higher the final manufacturing technology efficiency, and the longer the fluctuations in the evolution of manufacturing technology efficiency.

Through the above case analysis, we can see that when manufacturing technology converges to information technology, the dissipating force $\left(\beta_2 - \frac{\gamma_1\gamma_2}{\beta_1}\right)y^2(t)$ of manufacturing technology development can be reduced by improving the fusion of technology; at the same time driving force $\left(\alpha_2 + \frac{\gamma_2\alpha_1}{\beta_1} + 1\right)y(t)$ of manufacturing technology development can be improved. This makes the gap between the driving force and the dissipating force of manufacturing technology development smaller. Therefore, when enterprises increase the Manufacturing Technology Efficiency Development Potential Coefficient through investment, it is easier to make the driving force and dissipating force of the manufacturing technology development reach the same state, making it easier for the enterprises to fall into chaos, as shown in Figs. 20 and 23. In addition, due to the increase in technology fusion, the dissipating factor $\left(\beta_2 - \frac{\gamma_1\gamma_2}{\beta_1}\right)$ becomes smaller, while the driving coefficient $\left(\alpha_2 + \frac{\gamma_2\alpha_1}{\beta_1} + 1\right)$ becomes larger. Therefore, the steady state of manufacturing technology development $y(t) = \frac{\alpha_2 + \frac{\gamma_2\alpha_1}{\beta_1}}{\beta_2 - \frac{\gamma_1\gamma_2}{\beta_1}}$ becomes larger with the increase in technology fusion, as shown in Fig. 25. When the development of manufacturing technology has entered a mature period, the investment of

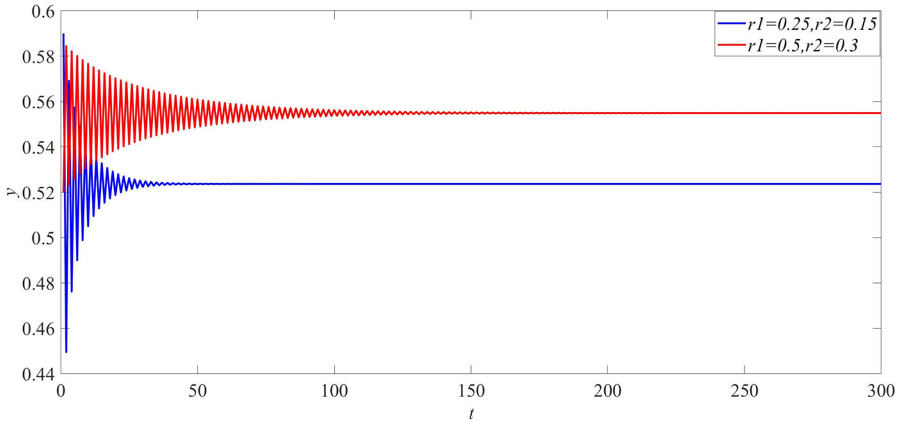


Fig. 25 The influence of technology fusion state on the development of manufacturing technology

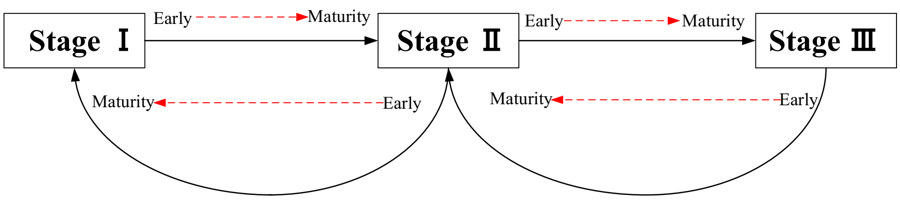


Fig. 26 Dynamics of technology fusion

enterprises in manufacturing technology will make the driving force and dissipating force of manufacturing technology development fiercely competitive, causing fluctuations and even chaos for enterprises in the development of manufacturing technology, as shown in Figs. 21 and 24. Therefore, when enterprise technology fusion reaches the maturity state, the enterprise needs to start a new development stage through enterprise transformation.

Through the above analysis, we find that robustness plays an important role in the development of technology fusion. The technology integration and collaborative development of an enterprise must be on the premise of robust or weakly robust operation. Nonrobust or chaotic state is fatal to the development of enterprise fusion. There are two reasons: (1) The development of an enterprise in a not robust state is unstable. At this time, any small decision of the enterprise may make the enterprise development enter a different development direction or even fall into a dilemma. (2) Development in a not robust and chaotic state is a great challenge for the management of the enterprise. It may cause that although the enterprise invests a lot of capital to introduce high-level technical personnel and new technologies, the technology efficiency is not improved, resulting in a waste of resources. In addition, such investment may have a great impact on the capital flow of the enterprise and even lead to a bankruptcy crisis in the operation of the enterprise.

Through Fig. 26, we give a systematic explanation of the relationship between the dynamics and system robustness at different stages of technology fusion. The technology fusion system studied in this paper is a dissipative system. When the driving force and the dissipating force are equal, the technological fusion or development of the enterprise will fall into chaos. Therefore, enterprises must avoid chaos in technological fusion or development. However, avoiding chaos does not require technological fusion or development to be in a stable state and maintain the robustness of the system. Rather, it requires that the technology fusion system enters a new stage of fusion before it enters chaos. The advantage of doing so is to avoid chaos and prevent the enterprise's technological fusion from stagnating and triggering a bankruptcy crisis. After the technology fusion system enters a new stage, the technology fusion or development will always undergo a transition from the early stage to the mature period. After the enterprise technology reaches the mature period, technological reforms must be carried out to make the technology fusion system enter the next stage of technology fusion. Therefore, the robustness of this paper mainly reflects the maintenance of the stability of the transitional stage from the early stage to the mature period.

7 Discussion

This paper conducts technology fusion research of information technology and manufacturing technology from a systematic perspective. The research on technology fusion in this paper focuses more on the binary relationship between information technology and manufacturing technology. Through the analysis of the characteristics of information technology and manufacturing technology, the trajectories and dynamic process of technology fusion are studied in stages, and the test results verify the feasibility of the method proposed in this paper. It is worth noting that the essence of technology fusion is a process in which driving force and dissipating force compete. Therefore, the process of technology fusion may fall into chaos. Therefore, when using enterprise technology fusion data to test the feasibility of the model, it must be satisfied that the initial technology fusion data are nonchaotic data. If it is chaotic data, it is necessary to reconstruct the phase space of the data. The reason why the tested results are achieved is that the initial evolution data are nonchaotic data; otherwise, the initial data need to be reconstructed in phase space, and the reconstructed data are used for testing.

Although this paper has made up for the lack of current literature research, it still has the following problems and shortcomings, which can be used as the direction of further research in the future:

1. Research on Judging the Future Development Direction of Technology Fusion Signal. The research on technology fusion in this paper mainly focuses on the observational research on the fusion starting point and the fusion process. There is no in-depth study on how to judge the critical state of fusion, and there is relatively little research on how the fusion signal will develop in the future, which can be used as the focus of further research.
2. Research on Reasonable Data Set Construction Method. This paper points out that there may be chaotic characteristics in the process of technology fusion. Therefore, when using enterprise technology fusion data for research, it is necessary to perform chaotic analysis on the data. If it is chaotic data, phase space reconstruction is required.
3. Research on Recognition of Specific Fusion Technology Direction. The research on technology fusion in this paper is mainly through mapping the technology fusion process into a time series, then establishing a dynamic evolution model for the time series, and then analyzing the evolution process. Compared with the refinement of the actual enterprise technology fusion process, this mapping has a larger granularity and does not fully reflect the specific technical direction. In the future, we can consider how to conduct more fine-grained fusion technology direction recognition research.

8 Conclusions

In this paper, we study the robustness of the technology fusion system. Our work emphasizes the necessity of robust strategy with phased fusion, as it reduces the enterprise investment costs and promotes the improvement of enterprise technical efficiency. After obtaining the order parameter equation of the technology fusion system, we discuss the performance of the system robustness of the two-dimensional technology fusion model. The results show that technology fusion will experience not robust state, robust state, weak robust state, and even chaotic state at different stages. When the technology fusion of the enterprise is in a robust state, not only the technical efficiency satisfies the expectations of the enterprise, but also the evolution process is stable. That means the investment of the enterprise can obtain the stable and expected return of the enterprise. Technology integration is in a not robust state, technical efficiency cannot satisfy the expectations of the enterprise, or the evolution process is unstable. At this stage, the investment of the enterprise will not obtain the expected return, which is not conducive to the development of its enterprise. When the technology fusion of the enterprise is in a weak robust state, although the technical efficiency will satisfy the expectations of the enterprise, the small decision errors at the bifurcation point can make the evolution of technology fusion enter a completely different path. Although the investment of the enterprise can obtain the expected return at this stage, it has certain uncertainty. When the technology fusion of the enterprise is in a chaotic state, the decision makers of the enterprise cannot make the correct choice of the direction of the technology fusion. At this stage, the investment income of the enterprise is completely uncertain, which is very unfavorable to the development of the enterprise and may bring bankruptcy crisis to the enterprise. Therefore, enterprise decision makers ensure that technology fusion is maintained in a robust state when investing. At this time, enterprise investment can bring stable returns that satisfy the development requirements of the enterprise. In addition, we also found that by increasing the degree of technology integration and collaborative development, enterprises can effectively improve the information technology efficiency or manufacturing technology efficiency when investing in information technology or manufacturing technology and reduce the cost of enterprise investment in the technology development stage. In the stage of technology integration and collaborative development, increasing the gap of the integration or dynamic collaborative development between manufacturing technology and information technology, enterprises may effectively improve the manufacturing technology efficiency and reduce the investment cost. The results of this paper can provide a reference for manufacturing enterprises to effectively promote technology fusion.

Remark (1) For enterprises, the technology fusion system is an open and complex system, and there are nonlinear interactions between different technologies in the development process of technology fusion. And in the process of technology fusion, it is necessary to exchange information and materials with the outside world and develop at the cost of resource consumption. Therefore, the technology fusion system has the characteristics of a dissipative structure. Therefore, only by adopting a system perspective can we more accurately and comprehensively understand and master the operating mechanism and dynamic characteristics of technology fusion. (2) The technology fusion of enterprises is the technological cooperation between different industries for enterprises to pursue benefits and produce products that meet consumer needs. The resource input of the enterprise is the driving force for the development of technology fusion, and the competition for technical resources in different fields within the enterprise and the social environment restrictions is the dissipating force. Enterprise technology fusion system will develop in the process of competition between the driving force and the dissipating force. For enterprises, dissipating force is widespread and inevitable. Therefore, in the development process of technology fusion, enterprises must continue to provide the driving force for technological fusion through resource input. Otherwise, if the driving force is significantly less than the dissipating force, the enterprise will eventually toward bankruptcy. However, when enterprises continue to consume resources, due to the competition between driving and dissipating force, the development of enterprise technology fusion begins to change, until it turns into chaos. Therefore, at this time, chaos can only be avoided by making the enterprise's technological fusion enter the next stage. Therefore, this is the reason why the technology fusion in this paper should be developed alternately at different stages.

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Compliance with ethical standards

Conflict of interest No conflict of interest exists in the submission of this manuscript.

Appendix I

The above $x_t \to x_2 (t \to \infty)$ is single-cycle convergence, and $x_{2t} \to x_1^*, x_{2t+1} \to x_2^* (t \to \infty)$ is 2 times period convergence.

Two times period stability analysis process:

$$\begin{aligned} x_{2t+1} &= f(x_{t+1}) = f(f(x_t)) = f \circ f(x_t) \\ &= \left(\alpha_1 + \frac{\gamma_1 \alpha_2}{\beta_2} + 1\right)\left[\left(\alpha_1 + \frac{\gamma_1 \alpha_2}{\beta_2} + 1\right)x_t + \left(\frac{\gamma_1 \gamma_2}{\beta_2} - \beta_1\right)x_t^2\right] \\ &\quad + \left(\frac{\gamma_1 \gamma_2}{\beta_2} - \beta_1\right)\left[\left(\alpha_1 + \frac{\gamma_1 \alpha_2}{\beta_2} + 1\right)x_t + \left(\frac{\gamma_1 \gamma_2}{\beta_2} - \beta_1\right)x_t^2\right]^2 \end{aligned}$$

let

$$\begin{aligned} x &= f(x) = f(f(x)) = f \circ f(x) \\ &= \left(\alpha_1 + \frac{\gamma_1 \alpha_2}{\beta_2} + 1\right)\left[\left(\alpha_1 + \frac{\gamma_1 \alpha_2}{\beta_2} + 1\right)x + \left(\frac{\gamma_1 \gamma_2}{\beta_2} - \beta_1\right)x^2\right] \\ &\quad + \left(\frac{\gamma_1 \gamma_2}{\beta_2} - \beta_1\right)\left[\left(\alpha_1 + \frac{\gamma_1 \alpha_2}{\beta_2} + 1\right)x + \left(\frac{\gamma_1 \gamma_2}{\beta_2} - \beta_1\right)x^2\right]^2 \end{aligned}$$

we can obtain 4 fixed points: $x_1^*, x_2^*, x_3^*, x_4^*$ and the stability of the system in the 2 times period can be obtained by $|f'(f(x))|_{x=x_i^*} < 1 (i \in \{1, 2, 3, 4\})$.

In the same way, the stability analysis of 4 times period, 8 times period, and 2^n times period can be obtained:

$$x_{2^n t+1} = f^{(2^n)}(x_t) = \underbrace{f \ldots f(x_t)}_{2^n}$$

When $n > 2$, there is no analytical solution, so it can only be obtained by computer approximation. And as n gets bigger, there will be chaos.

Appendix II

After the stability analysis of the above order parameter equation, let us take a look at the doubling period stability of the order parameter equation. When the value of α_2 jumps out of the above constraint, y_1 or y_2 is no longer stable. If the value of α_2 deviates slightly from $-\frac{\gamma_1 \alpha_2}{\beta_2}$ or $2 - \frac{\gamma_2 \alpha_1}{\beta_1}$, although $\{y_t\}$ no longer converges to y_2 or y_1, two subsequences y_1^*, y_2^* appear and satisfy $y_{2t} \to y_1^*, y_{2t+1} \to y_2^* (t \to \infty)$. The above $y_t \to y_2 (t \to \infty)$ is single-cycle convergence, and $y_{2t} \to y_1^*, y_{2t+1} \to y_2^* (t \to \infty)$ is 2 times period convergence.

Two times period stability analysis process:

$$\begin{aligned} y_{2t+1} &= f(y_{t+1}) = f(f(y_t)) = f \circ f(y_t) \\ &= \left(\alpha_2 + \frac{\gamma_2 \alpha_1}{\beta_1} + 1\right)\left[\left(\alpha_2 + \frac{\gamma_2 \alpha_1}{\beta_1} + 1\right)y_t + \left(\frac{\gamma_1 \gamma_2}{\beta_1} - \beta_2\right)y_t^2\right] \\ &\quad + \left(\frac{\gamma_1 \gamma_2}{\beta_1} - \beta_2\right)\left[\left(\alpha_2 + \frac{\gamma_2 \alpha_1}{\beta_1} + 1\right)y_t + \left(\frac{\gamma_1 \gamma_2}{\beta_1} - \beta_2\right)y_t^2\right]^2 \end{aligned}$$

let

$$\begin{aligned} y &= f(y) = f(f(y)) = f \circ f(y) \\ &= \left(\alpha_2 + \frac{\gamma_2 \alpha_1}{\beta_1} + 1\right)\left[\left(\alpha_2 + \frac{\gamma_2 \alpha_1}{\beta_1} + 1\right)y_t + \left(\frac{\gamma_1 \gamma_2}{\beta_1} - \beta_2\right)y_t^2\right] \\ &\quad + \left(\frac{\gamma_1 \gamma_2}{\beta_1} - \beta_2\right)\left[\left(\alpha_2 + \frac{\gamma_2 \alpha_1}{\beta_1} + 1\right)y_t + \left(\frac{\gamma_1 \gamma_2}{\beta_1} - \beta_2\right)y_t^2\right]^2 \end{aligned}$$

we can obtain 4 fixed points $y_1^*, y_2^*, y_3^*, y_4^*$ and the stability of the system in the 2 times period can be obtained by $|f'(f(y))|_{y=y_i^*} < 1 (i \in \{1, 2\})$. In the same way, the stability analysis of 4 times period, 8 times period, and 2^n times period can be obtained:

$$y_{2^n t+1} = f^{(2^n)}(y_t) = \underbrace{f \cdots f(y_t)}_{2^n}$$

When $n > 2$, there is no analytical solution, so it can only be obtained by computer approximation. And as n gets bigger, there will be chaos.

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