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Evolution of technology management system based on self-organization theory

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Abstract: Industrial and academic interest in how to effectively manage technology resources is increasing as it becomes more and more important. Effective managing of technology resources depends on technology management system, and thus understanding how such system evolves becomes an ongoing research topic. Based on the self-organization theory, this paper constructs an evolution model of technology management system. The simulation results show that the evolution of each of the technology management subsystem is affected by the knowledge growth rate of its own, and it is also affected by the coupling and synergy relationship with other subsystems. Moreover, the coupling and synergy relationship can make the speed of evolution higher than the knowledge growth rate of the subsystem itself.

Keywords: technology management, technology management system, self-organization.

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1. Introduction

Nowadays, technological changes become more and more rapid as the competitive environment becomes more dynamic, varying, and turbulent. In such circumstance, it is widely accepted that firms' competitive strategies are increasingly becoming technology-driven [1]. In order to achieve such competitive strategies, firms are more and more dependent on technology management, which can help firms to capture new opportunities generated by technological changes, and further convert these opportunities into value [2]. Technology management involves all management activities associated with technology, and thus it is a system with a number of elements [3]. It is extremely important for academics and practitioners to get a better understanding of technology management system.

Researchers have investigated technology management system from different perspectives. For instance, National Research Council defined technology management as "a process, which includes planning, directing, control and coordination of the development and implementation of technological capabilities to shape and accomplish the strategic and operational objectives of an organization" [4]. This definition shows that the technology management system combines both "hard" aspects of technology and "soft" aspects of management. Drejer argued that technology management is evolved from R&D management, through innovation management and technology planning before developing as strategic management of technology [5]. This classification indicates that the technology management system involves multiple tasks, including R&D management, innovation management, technology planning and technology strategy. Phaal et al. proposed that an effective system for managing technology in complex business environments requires a number of technology management tools and processes [6]. Therefore, they construct a catalogue, which includes tools and processes that are implemented in management of technology. Cetindamar et al. argued that the technology management system was based on technology management activities, and they identified six core technology management activities in the technology management system, including identification, selection, acquisition, exploitation, protection, and learning [2].

Although there are some research focusing on the technology management system, they only explore the elements of the technology management system. The major obstacle is that we still have insufficient understanding about how the technology management system evolves. With the increasing complexity of technology, firms must

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evolve their technology management systems to achieve the best performance [7]. While the research on the evolution of technology management system is rather limited, which leaves it in a black box. This paper aims to investigate how technology management system evolves by using the self-organization theory as the theoretical foundation. The self-organization theory can provide an abstract and general description of evolutionary processes [8], which has been extensively used in management research [9,10].

The remainder of this paper proceeds as follows. Section 2 develops the theoretical analysis of this paper. Section 3 shows the mathematical formulation. Section 4 presents the simulation results. The final section concludes with implications and limitations.

2. Theoretical analysis of technology management system and its evolution

2.1 Technology management system

It is generally believed that a system is composed by a set of elements that are interconnected, interdependent, and interactive to achieve the same goal [11]. Referring to the previous research [12], the technology management system can be defined as an integrated set of processes and activities that a firm uses to improve its technology competitiveness, and the elements of technology management can be divided into three categories, namely resource management, organization management and quality management [13]. Therefore, the technology management system includes three subsystems, which are technology resource management subsystem, technology organization management subsystem, and technology quality management subsystem.

The function of the technology resource management subsystem is to acquire, develop, gather, share, apply, and protect technology resources. Technology resources play a very important role in the development of a firm. The resource based view argues that a firm's sustained competitive advantage derives from the valuable, rare, inimitable, and non-substitutable resources it controls [14], and technology resources own these characteristics. The technology resources not only include tangible resources, such as equipment and funds, but also include intangible resources, such as personnel, information, and research outcomes [15]. Generally, different firms will adopt different management strategies according to the different technology resources they possess. Effective management of technology resources can significantly improve the technology performance of a firm.

The technology organization management subsystem is to manage the flow of technology resources and ensure that technology resources are used effectively and efficiently, which involves the design of organization structure, the assignment of tasks, the definition of personal responsibilities and so on. It is argued that the introduction of the technology resources must be compatible with the organization structure with aims to have less difficulty in accepting [16]. Moreover, the rapid changes in technology have made it important to accumulate technology resources, and this process will be facilitated by proper assignment of tasks and the definition of personal responsibilities [17]. Therefore, improving the maturity of the technology organization management subsystem can better help firms use technology resources to gain competitive advantage.

The technology quality management subsystem can guarantee the use of technology resources in the way it is planned. Technology quality management is a holistic management philosophy that fosters the continuing improvement through all functions of a firm [18]. Researchers have long emphasized the importance of technology quality management because it can help firms minimize non-value activities and reduce time and costs of technology development [19]. Technology quality management subsystem can provide various means for firms to determine the policy, objectives and responsibilities that relate to technology resources, and thus technology quality management subsystem could ensure firms to better survive.

2.2 Technology management system evolution

Technology management can be conceived as the development and exploitation of a firm's technological capability [4]. However, a firm's technological capability is not static, and thus the technology management should evolve accordingly [20]. Generally speaking, the evolution of technology management system is from low-level to high-level, which can lead a firm to transform its technology performance from low to high. From an internal perspective, the evolution of the technology management system can improve the efficiency of the use of technology resources, enabling firms to achieve the maximum output with limited resources. Additionally, the evolution of the technology management system can also help firms accumulate related technology resources and further form a technology resources base. The technology resources base can help firms develop a higher level technology management system. These two are the important achievements of the evolution of technology management system, and they are also the goals of the evolution of the technology management system.

From an external perspective, the evolution of the technology management system will meet the needs of the rapid technology changes. Each technology management subsystem must react to evolve, and the evolution of each technology management subsystem will further lead to the evolution of the technology management system. The evolution will result in the increasing of the maturity of each technology management subsystem, and the improvement of the cooperation among different technology management subsystems. Finally, the technology performance of a firm will increase with the evolution of the technology management system.

2.3 Knowledge ecology characteristics of technology management system

The knowledge ecosystem is a system in which different knowledge entities exchange their knowledge. Also, in a knowledge ecosystem, the knowledge entities can exchange their knowledge with external environment. This paper uses the knowledge ecosystem to explain the technology management system for the following reasons.

Firstly, the implementers of technology management are knowledge entities. The implementers of technology management are human beings who are the carriers of knowledge. They could accomplish the tasks of technology management by using their owned knowledge as well as the knowledge acquired from the outside. At the same time, the expansion of the functions of technology management system will involve more implementers, including not only the technology strategy makers at the strategic level, but also the operators of specific technology management activities at the operational level. As the complexity of the technology management tasks increases, the implementer should cooperate with each other to accomplish the tasks. While in the cooperation process, the knowledge flow and knowledge sharing will inevitably occur.

Secondly, technology management aims to develop and exploit technological capability, which is the technological knowledge that firms own [21]. Therefore, technology management can be regarded as the management of technological knowledge [22], a process of using old technological knowledge to create new technological knowledge. As a result, technology management, by making effective use of technological knowledge, can not only develop products, but also improve existing technological knowledge and generate new technological knowledge in response to the competitive business environment [23].

Thirdly, technology management has a close relationship with knowledge management. Cetindamar et al. proposed that there are six core technology management activities, namely identification, selection, acquisition, exploitation, protection, and learning [2]. All of these six core technology management activities have a close relationship with knowledge management. For instance, firms should identify the technological knowledge they need. After the selection based on a good grasp of strategic objectives and priorities developed at the business strategy level, firms then should acquire the selected technological knowledge through multiple sources, such as collaboration or external development. After acquisition, there is a need for exploitation of the acquired technological knowledge, and further protecting the newly generated technological knowledge. Finally, firms should involve reflections on technology management activities carried out within or outside the firm to learn from them.

Based on the analysis above, it can be concluded that the evolution of technology management system is a process of scanning, selecting, learning, and adapting to the technology changes through a series of knowledge management activities [24]. Therefore, the evolution of the technology management system can be analyzed from the perspective of knowledge ecology.

2.4 Self-organization evolution of technology management system

In the evolution process, the tasks undertaken by different technology management subsystems are different. The technology resource management subsystem is mainly responsible for the acquisition and allocation of technology resources. The technology organization management subsystem is mainly responsible for designing of the organization structure. The main task of the technology quality management subsystem is related to the quality control. The tasks of each technology management subsystem are different, so that each of them can operate independently under the guidance of the firm strategy. As a part of the technology management system, the evolution of each subsystem can promote the evolution of the entire technology management system. At the same time, the evolution of each subsystem can also affect the evolution of other subsystems, and the subsystems will also promote the evolution of their own systems through cooperation. Therefore, there exists a coupling and synergy relationship among the technology management subsystems.

For instance, at the initial stage of the evolution of technology resource management subsystem, it has fewer resources to be managed, and there is little knowledge related to technology resources management. At this stage, firms only rely on their own experience to manage the technology resources. Then, they will obtain feedbacks about whether their management activities are effective or not, and further conduct adaptive learning based on the feedback results to promote the evolution of technology resource management subsystem. In the evolution of technology organization management subsystem, firms can get knowledge from the environment, and then adjust the organization structure according the environment change. Moreover, with the maturity of technology organization management subsystem, firms can form a series of routines, which can be the solutions of certain problems. These routines will also be updated continuously according to the acquired knowledge. In the evolution of technology quality management subsystem, firms will conduct continuous knowledge searching and selection through quality management. At the same time, firms should also deal with problems caused by environment changes, which can further promote the evolution of technology quality management subsystem.

In the evolution process, different technology management subsystems have a coupling and synergy relationships [25]. Coupling means two or more subsystems are interdependent with each other to co-exist [26]. While synergistic between different subsystems will facilitate the evolution of the whole system [27]. Through the analysis above, it can be known that there exists inner linkage among technology resource management subsystem, technology organization management subsystem, and technology quality management subsystem, and the inner linkage is based on technology resources. To be specific, these three subsystems can cooperate with each other to employ technology resources. For example, technology resource management subsystem and technology organization management can cooperate with human resources. Firms with high levels of technology resource management can attract, select, and retain high quality employees. However, firms also need technology organization management to arrange the employees to the right positions and thus maximize the use of their abilities. Furthermore, technology organization management subsystem and technology quality management subsystem can also cooperate with human resources. Technology organization management can stimulate organizational learning, which motivates employees to find distinct methods and procedures to achieve innovation. Technology quality management can provide opportunities to apply quality management practices, which can ensure employees conform to the established requirements. Firms thus can deploy technology organization management and technology quality management to provide fertile environments for the involvement and commitment of employees. Therefore, different technology management subsystems could cooperate with each other to evolve.

2.5 Self-organization evolution mode of technology management system

The impetus of the self-organization evolution is the misfit between system and external environment. When the changes of external environment do not exceed the stability point of technology management system, it will maintain its original structure through self-stabilizing. However, when the changes of the external environment exceed the stability point of technology management system, it will become unstable. At this time, the multi-directional mutations occur. Through the selection of external environment and firm themselves, the mutations that are suitable for the environment changes will be selected, and then form a new technology management system. As a result, the technology management system evolves to a higher-level. The self-organization evolution mode of technology management system can be shown in Fig. 1.

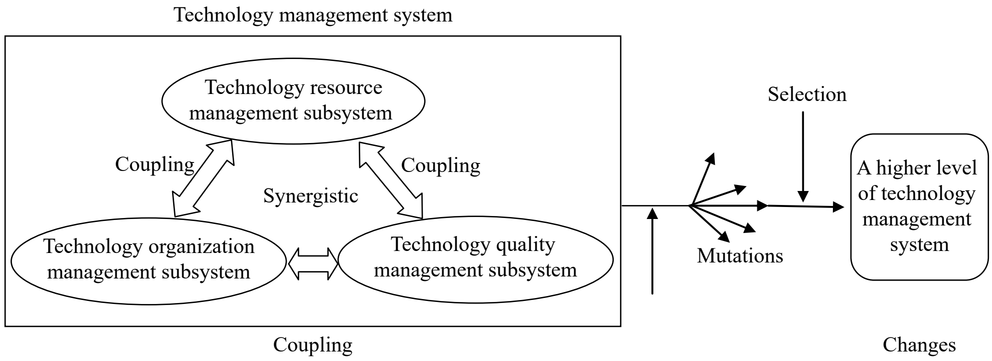


Fig. 1 Self-organization evolution mode of technology management system

3. Mathematical formulation of technology management system evolution

3.1 Nature evolution of technology management subsystems

Owing to the knowledge ecology characteristics of the technology management system, this paper uses the level of the knowledge stock to represent the development degreeoftechnologymanagementsubsystems.Thenatureevolution of technology management subsystems refers to the change rate of knowledge stock brought by each sub-system's own learning activities without co-evolution with other subsystems. Referring to previous research [28], the basic equation of knowledge stock is

$$\frac{\mathrm{d}Y(t)}{\mathrm{d}t} = [g(t) - d(t)]Y(t) \tag{1}$$

where $g(t)$ represents the growth rate of knowledge, $d(t)$ represents the decreasing rate of knowledge, and $Y(t)$ represents the level of knowledge stock at time t. This paper draws on the basic equation of knowledge stock to describe the nature evolution of technology management subsystems.

For technology resource management subsystem, there are two factors driving the evolution, namely resource utilization capability and resource acquisition capability. This paper uses ω_1 to represent the growth rate of knowledge brought by the driving factors, and uses γ_1 and γ_2 to represent the knowledge growth brought by resource utilization capability and resource acquisition ability capability respectively. At the same time, the knowledge of technology resource management subsystem will also decrease, which can be represented as

$$d_1(t) = \rho_1(\theta \mathrm{e}^{at})^r, \quad \rho_1 > 0;\ r > 0;\ a > 0;\ t > 0 \tag{2}$$

where ρ_1 represents the relationship between the knowledge of technology resource management subsystem and external knowledge.

Therefore, the knowledge change rate of the technology resource management subsystem at time t can be expressed as

$$\begin{aligned} \frac{\mathrm{d}Y_{I1}(t)}{\mathrm{d}t} &= [g_1(t) - d_1(t)]Y_1(t) + \Gamma_1 = \\ &[\gamma_1\omega_1 \cdot \gamma_2\omega_1 - \rho_1(\theta \mathrm{e}^{at})^r]Y_1(t) = \\ &[\gamma_1\gamma_2\omega_1{}^2 - \rho_1(\theta \mathrm{e}^{at})^r]Y_1(t) + \Gamma_1 \end{aligned} \tag{3}$$

where $g_1(t)=\gamma_1\gamma_2\omega_1{}^2$ represents the knowledge growth rate of technology resource management subsystem. $Y_1(t)$ represents the knowledge stock of technology resource management subsystem at time t. Γ_1 represents the random disturbance term in the evolution of technology resource management subsystem.

For technology organization management subsystem, there are two factors driving the evolution, namely firm informatization and firm standardization. Similarly, this paper uses ω_2 to represent the growth rate of knowledge brought by the driving factors and η_1 and η_2 to represent the knowledge growth brought by firm informatization and firm standardization respectively. The knowledge decreasing of technology organization management subsystem can be represented by

$$d_2(t) = \rho_2(\theta \mathrm{e}^{at})^r, \quad \rho_2 > 0;\ r > 0;\ a > 0;\ t > 0 \tag{4}$$

where ρ_2 represents the relationship between the knowledge of technology organization management subsystem and external knowledge.

Therefore, the knowledge change rate of the technology organization management subsystem at time t can be expressed as

$$\begin{aligned} \frac{\mathrm{d}Y_{I2}(\mathrm{t})}{\mathrm{d}t} &= [g_2(t) - d_2(t)]Y_2(t) + \Gamma_2 = \\ &[\eta_1\omega_2 \cdot \eta_2\omega_2 - \rho_2(\theta \mathrm{e}^{at})^r]Y_2(t) = \\ &\eta_1\eta_2\omega_2{}^2 Y_2(t) - \rho_2(\theta \mathrm{e}^{at})^r Y_2(t) + \Gamma_2 \end{aligned} \tag{5}$$

where $g_2(t)=\eta_1\eta_2\omega_2{}^2$ represents the knowledge growth rate of technology organization management subsystem. $Y_2(t)$ represents the knowledge stock of technology organization management subsystem at time t. Γ_2 represents the random disturbance term in the evolution of technology organization management subsystem.

For technology quality management subsystem, there are three factors driving the evolution, namely quality management capability, management support and risk management capability. Similarly, this paper uses ω_3 to represent the growth rate of knowledge brought by the driving factors, and uses δ_1, δ_2, and δ_3 to represent the knowledge growth brought by quality management capability, management support and risk management capability respectively. The knowledge decreasing of technology quality management subsystem can be represented as

$$d_3(t) = \rho_3(\theta \mathrm{e}^{at})^r, \quad \rho_3 > 0;\ r > 0;\ a > 0;\ t > 0 \tag{6}$$

where ρ_3 represents the relationship between the knowledge of technology quality management subsystem and external knowledge.

Therefore, the knowledge change rate of the technology quality management subsystem at time t can be expressed as

$$\begin{aligned} \frac{\mathrm{d}Y_{I3}(\mathrm{t})}{\mathrm{d}t} &= [g_3(t) - d_3(t)]Y_3(t) + \Gamma_3 = \\ &[\delta_1\omega_3 \cdot \delta_2\omega_3 \cdot \delta_3\omega_3 - \rho_3(\theta \mathrm{e}^{at})^r]Y_3(t) = \\ &\delta_1\delta_2\delta_3\omega_3{}^3 Y_3(t) - \rho_3(\theta e^{at})^r Y_3(t) \end{aligned} \tag{7}$$

where $g_3(t)=\delta_1\delta_2\delta_3\omega_3{}^3$ represents the knowledge growth rate of technology quality management subsystem. $Y_3(t)$ represents the knowledge stock of technology quality management subsystem at time t. Γ_3 represents the random disturbance term in the evolution of technology quality management subsystem.

3.2 Cooperation of technology management subsystems

During the evolution of the technology management system, the cooperation between the subsystems also affects the development of technology management system. From the perspective of knowledge, the cooperation between the subsystems will bring the increasing of knowledge stock. It is argued that cooperation in the knowledge network follows $F=g(k\mathrm{e}^{\beta r}, r)$, and the evolution can be expressed as

$$x_i(t)=\sum a_i(t)\cdot \mathrm{e}^{\beta_i(t)\cdot(x_j-x_i)}\cdot x_j(t)+\theta(t) \tag{8}$$

where $x_i(t)$ represents the knowledge output level of node i at time t. $a_i(t)$ represents the knowledge stock of node i at time t. β_i represents the mutual influence coefficient of node i and node j. x_j-x_i represents the knowledge potential difference of these two nodes.

The evolution of technology management subsystems can be described by this equation because of the knowledge ecology characteristics of technology management system. In addition, from the analysis above, we can know that different subsystems have coupling and synergy relationships. As a result, this paper introduces the coupling coefficient and synergy coefficient to describe the evolution of technology management subsystems. The knowledge change rate caused by the cooperation between subsystems can be shown as

$$\frac{\mathrm{d}Y_c(t)}{\mathrm{d}t}=\sum Y_i(t)\cdot[\mathrm{e}^{\beta_{ij}(\omega_j-\omega_i)}\cdot(k_i\omega_i+k_j\omega_j)+ \mathrm{e}^{\alpha_{ij}(\omega_j-\omega_i)}(p_i\omega_i+p_j\omega_j)] \tag{9}$$

where k_i and k_j represent the ratio of knowledge resources that can generate effective cooperation between subsystems. p_i and p_j represent the ratios of knowledge resources that effectively cooperate between subsystems. β_{ij} indicates the synergy willingness between technology management subsystems. α_{ij} indicates the coupling willingness between technology management subsystems. $\omega_j-\omega_i$ represents the difference between the knowledge growth rate of the two technology management subsystems.

3.3 Model of the self-organization evolution of technology management system

As the evolution of technology management system is driven by the evolution of each subsystem, by combining the above equations, the model of the self-organization evolution of technology management system can be obtained, which can be shown as

$$\begin{cases}\dfrac{\mathrm{d}Y_i}{\mathrm{d}t}=\dfrac{\mathrm{d}Y_{Ii}}{\mathrm{d}t}+\dfrac{\mathrm{d}Y_c(t)}{\mathrm{d}t}, \quad i=1,2,3\\ \dfrac{\mathrm{d}Y_{I1}(\mathrm{t})}{\mathrm{d}t}=[g_1(t)-d_1(t)]Y_1(t)+\varGamma_1\\ g_1(t)=\gamma_1\gamma_2{\omega_1}^2\\ d_1(t)=\rho_1(\theta\mathrm{e}^{at})^r\\ \dfrac{\mathrm{d}Y_{I2}(t)}{\mathrm{d}t}=[g_2(t)-d_2(t)]Y_2(t)+\varGamma_2\\ g_2(t)=\eta_1\eta_2{\omega_2}^2\\ d_2(t)=\rho_2(\theta\mathrm{e}^{at})^r\\ \dfrac{\mathrm{d}Y_{I3}(\mathrm{t})}{\mathrm{d}t}=[g_3(t)-d_3(t)]Y_3(t)+\varGamma_3\\ g_3(t)=\delta_1\delta_2\delta_3{\omega_3}^3\\ d_3(t)=\rho_3(\theta\mathrm{e}^{at})^r\\ \dfrac{\mathrm{d}Y_c(t)}{\mathrm{d}t}=\\ \sum Y_i(t)\cdot[\mathrm{e}^{\beta_{ij}(\omega_j-\omega_i)}\cdot(k_i\omega_i+k_j\omega_j)-\mathrm{e}^{\alpha_{ij}(\omega_j-\omega_i)}(p_i\omega_i+p_j\omega_j)],\\ i,j=1,2,3\end{cases} . \tag{10}$$

After calculation, the final model is

$$\begin{cases}\dfrac{\mathrm{d}Y_1}{\mathrm{d}t}=Y_1(t)(\gamma_1\gamma_2{\omega_1}^2-\rho_1\theta\mathrm{e}^{art})+\\ [(\mathrm{e}^{\beta_{12}(\omega_2-\omega_1)}(k_1\omega_1+k_2\omega_2)+\mathrm{e}^{\alpha_{12}(\omega_2-\omega_1)})\cdot(p_1\omega_1+p_2\omega_2)+\\ (\mathrm{e}^{\beta_{13}(\omega_3-\omega_1)}(k_1\omega_1+k_3\omega_3)+\mathrm{e}^{\alpha_{13}(\omega_3-\omega_1)})\cdot(p_1\omega_1+p_3\omega_3)]\}+\varGamma_1\\ \dfrac{\mathrm{d}Y_2}{\mathrm{d}t}=Y_2(t)\{(\eta_1\eta_2{\omega_2}^2-\rho_2\theta\mathrm{e}^{art})+\\ [(\mathrm{e}^{\beta_{12}(\omega_2-\omega_1)}(k_1\omega_1+k_2\omega_2)+\mathrm{e}^{\alpha_{12}(\omega_2-\omega_1)})\cdot(p_1\omega_1+p_2\omega_2)+\\ (\mathrm{e}^{\beta_{23}(\omega_3-\omega_2)}(k_2\omega_2+k_3\omega_3)+\mathrm{e}^{\alpha_{23}(\omega_3-\omega_2)})\cdot(p_2\omega_2+p_3\omega_3)]\}+\varGamma_2\\ \dfrac{\mathrm{d}Y_3}{\mathrm{d}t}=Y_3(t)\{(\delta_1\delta_2\delta_3{\omega_3}^3-\rho_3\theta\mathrm{e}^{art}+\\ [(\mathrm{e}^{\beta_{13}(\omega_3-\omega_1)}\cdot(k_1\omega_1+k_3\omega_3)+\mathrm{e}^{\alpha_{13}(\omega_3-\omega_1)})(p_1\omega_1+p_3\omega_3)+\\ (\mathrm{e}^{\beta_{23}(\omega_3-\omega_2)}(k_2\omega_2+k_3\omega_3)+\mathrm{e}^{\alpha_{23}(\omega_3-\omega_2)})\cdot(p_2\omega_2+p_3\omega_3)]\}+\varGamma_3\\ \beta_{ij}>0,\ \alpha_{ij}>0,\quad i,j=1,2,3\\ 0\leqslant k_1,k_2,k_3,p_1,p_2,p_3,\rho_1\rho_2,\rho_3,\gamma_1,\gamma_2,\eta_1,\eta_2,\delta_1,\delta_2,\delta_3\leqslant 1\\ \theta,a,r>0\\ Y_1|_{t=0}=Y_{1(0)}=1\\ Y_2|_{t=0}=Y_{2(0)}=1\\ Y_3|_{t=0}=Y_{3(0)}=1\end{cases} . \tag{11}$$

Due to the nonlinear constraints of the equation, the above equation is a non-holonomic dynamic model, and it requires computer software to solve. Using Matlab for simulation can achieve fast and accurate solutions. This paper thus uses Matlab to simulate.

4. Simulation results

In order to reduce the complexity of the simulation, some parameters in the model are simplified to a certain value. For instance, we set the knowledge decreasing as a fixed value, namely $d_1(t)$, $d_2(t)$, and $d_3(t)$ are constant. At the same time, it is assumed that the knowledge resources that can generate effective collaboration between subsystems will not change significantly within a period of time. Thus, k_1, k_2, and k_3 are set as fixed values. In order to facilitate the observation of the evolution trend of each subsystem, the evolution trajectory of the technology resource management subsystem is represented by the black "+" curve, the evolution trajectory of the technology organization management subsystem is represented by the blue "*", and the evolution trajectory of the technology quality management subsystem is represented by the blue straight line.

We first simulate the evolution of the subsystem itself when there is no coupling and synergy. The knowledge growth rates of the three subsystems are set as (0.5, 0.4, 0.3), (0.5, 0.3, 0.7), and (0.3, 0.2, 0.7) respectively. The results are shown in Fig. 2.

It can be seen that, without the consideration of coupling and synergy, the influence of the subsystem's knowledge growth rate on the evolution of technology management system is mainly manifested in the speed of evolution. Compare Fig. 2(a) and Fig. 2(b) and it can be seen that when the growth rate of the technology quality management subsystem increases significantly, its evolution speed also accelerates significantly. Comparing Fig. 2(b) and Fig. 2(c), it can be seen that when the knowledge growth rate of technology resource management subsystem and the knowledge growth rate of technology organization management subsystem decrease, their evolution speed also significantly decreases. At the same time, it can be seen from Fig. 2(c) that when the knowledge growth rate of technology resource management subsystem and the technology organization management subsystem is particularly low, the evolution speed of these two subsystems is also particularly slow. In summary, it can be seen that the higher the knowledge growth rate of technology management subsystem itself, the faster the evolution of the subsystem. When the knowledge growth rate is too low, the subsystem will fail to evolve or even decline.

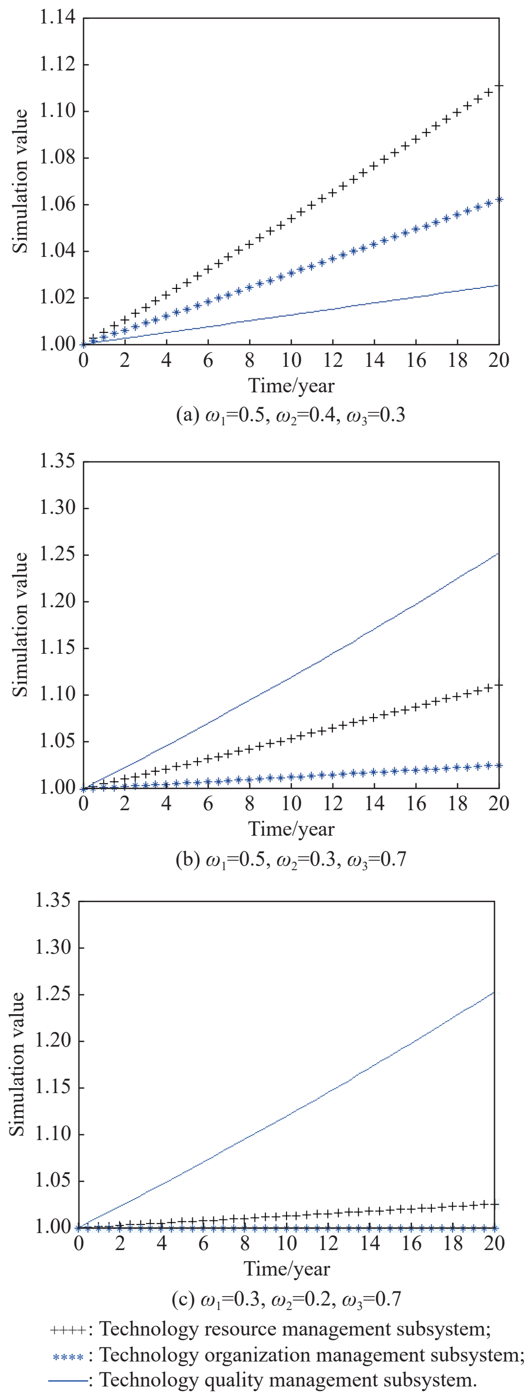


Fig. 2 Influence of subsystem's knowledge growth rate on evolution of technology management system without consideration of coupling and synergy

Then, simulate the evolution of the subsystem under the consideration of coupling and synergy. The knowledge growth rates of the three subsystems are set as (0.5, 0.4, 0.3), (0.5, 0.3, 0.7), and (0.3, 0.2, 0.7) respectively, and the cooperation willingness is set as 0.1. The results are shown in Fig. 3.

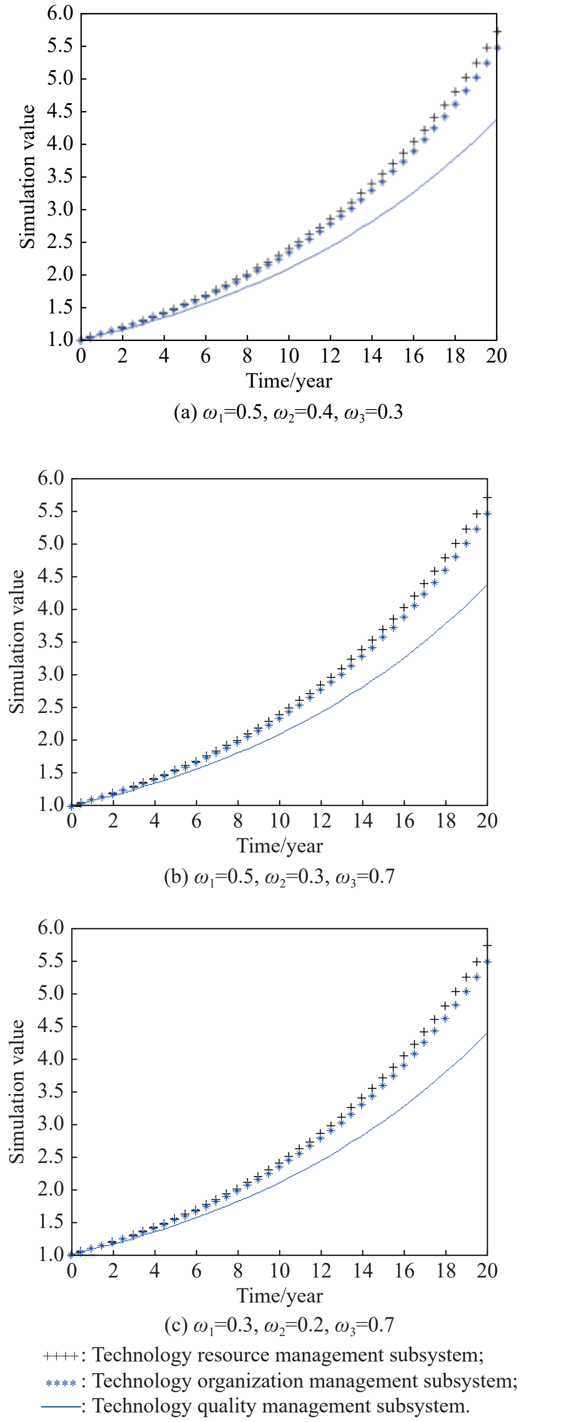
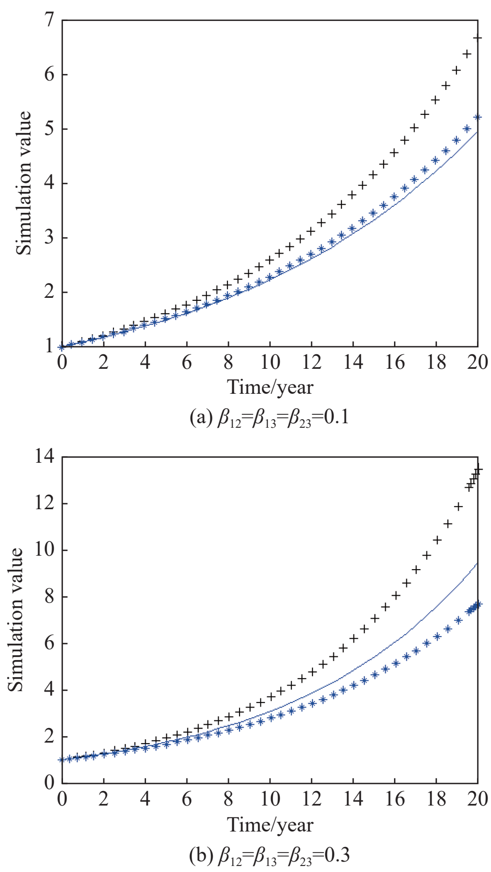


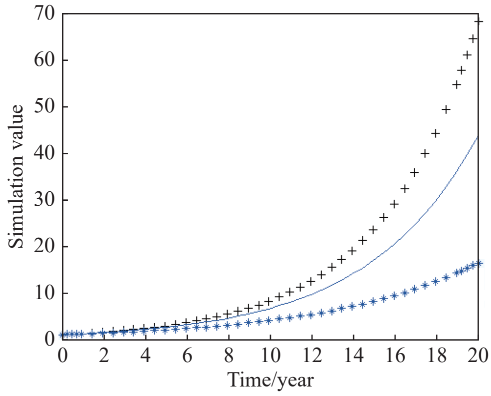
Fig. 3 Influence of subsystem's knowledge growth rate on evolution of technology management system with consideration of coupling and synergy

Compare the results of Fig. 2 and Fig. 3. Although the knowledge growth rates of the three subsystems are the same, the evolution trajectory is changed. For example, comparing Fig. 2(a) and Fig. 3(a), it can be found that the evolution trajectory is closer when considering the coupling and synergy. This indicates that the evolution of different subsystems will influence each other to make the evolution speed of each subsystem maintain a relatively similar state, which is further conducive to the coupling and synergy between subsystems. At the same time, by comparing the values on the vertical axis, it can be found that the evolution of the subsystem has been greatly improved through the coupling and synergy. We can draw the similar conclusion when comparing Fig. 2(b) and Fig. 3(b) and comparing Fig. 2(c) and Fig. 3(c).

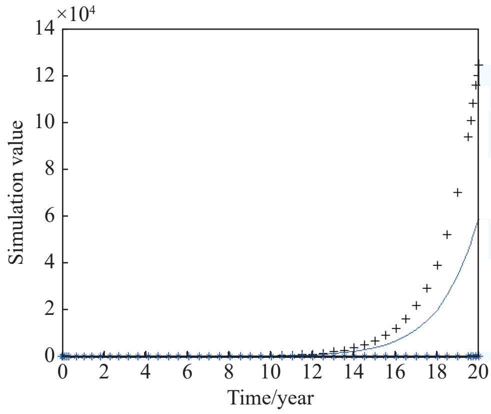
Through the analysis of Fig. 3, it can be found that the cooperation willingness will affect the evolution of technology management system. Therefore, we next simulate how cooperation willingness affects the evolution of technology management system. The simulation can be divided into two situations. Firstly, the cooperation willingness of the three subsystems is the same. The knowledge growth rates of the three subsystems are set as (0.5, 0.4, 0.3). The results are shown in Fig. 4.

By comparing the four figures in Fig. 4, it can be found that with the increasing of the cooperation willingness, the evolution speed has also been significantly improved. This indicates that the cooperation willingness will promote the evolution of technology management system.





(c) β_{12}=β_{13}=β_{23}=0.6

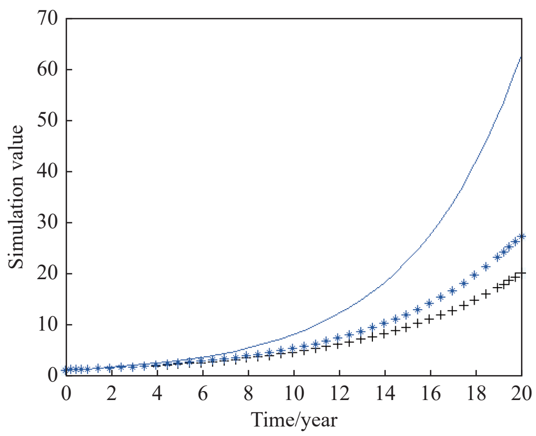


(d) β_{12}=β_{13}=β_{23}=1.2

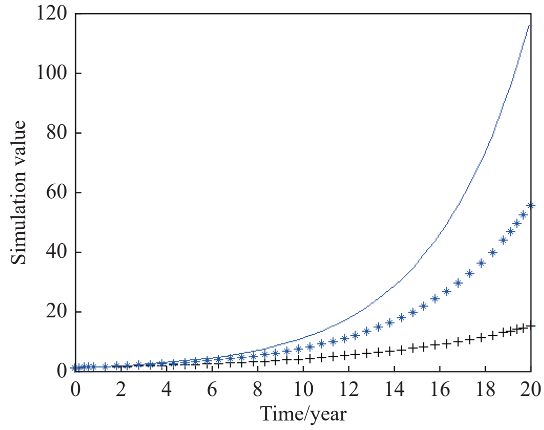
++++: Technology resource management subsystem;
****: Technology organization management subsystem;
——: Technology quality management subsystem.

Fig. 4 Influence of cooperation willingness when they are the same

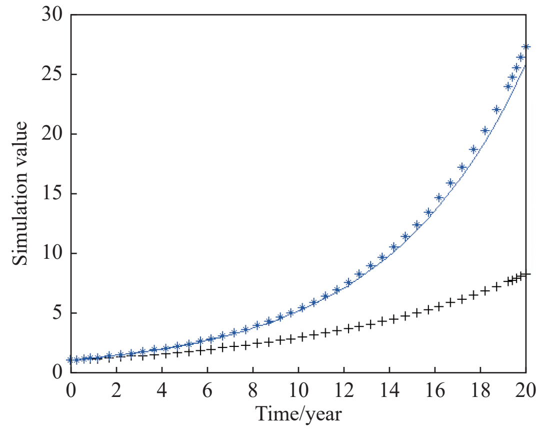
Secondly, the cooperation willingness of the three subsystems is not the same. The knowledge growth rates of the three subsystems are set as (0.5, 0.4, 0.3). The results are shown in Fig. 5.



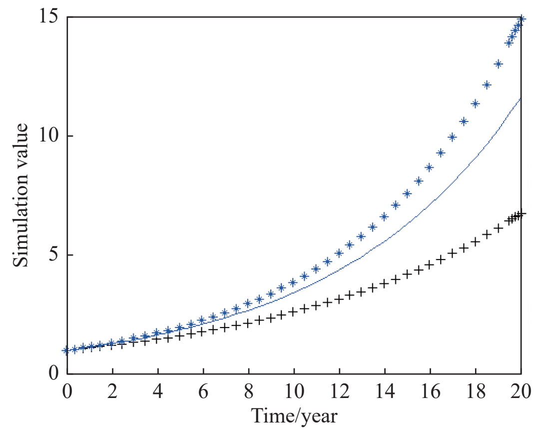
(a) β_{12}=0.2, β_{13}=0.9, β_{23}=1.2



(b) β_{12}=0.1, β_{13}=0.8, β_{23}=1.5



(c) β_{12}=0.2, β_{13}=0.3, β_{23}=1.2



(d) β_{12}=0.2, β_{13}=0.1, β_{23}=0.9

++++: Technology resource management subsystem;
****: Technology organization management subsystem;
——: Technology quality management subsystem.

Fig. 5 Influence of cooperation willingness when they are not the same

Compare Fig. 4(a) and Fig. 4(c) and it can be found that when cooperation willingness of technology resource management subsystem and technology quality management subsystem is unchanged, the cooperation willingness of technology organization management subsystem changes. The evolution trajectory of each subsystem has also undergone significant changes. Comparing the vertical axis values of these two graphs, it can be found that the evolution speed of technology quality management subsystem slows down significantly. Compare the values of the vertical axis in Fig. 4(a) and Fig. 4(b), it can be found that when the cooperation willingness of technology organization management subsystem and technology quality management subsystem increases, the evolution speed of these two subsystems is significantly improved. Compare Fig. 4(a), Fig. 4(b), Fig. 4(c) and Fig. 4(d) and it can be found that when the cooperation willingness of the subsystems is high, the evolution speed of the subsystems is faster. While when the cooperation willingness of the subsystems is low, the evolution speed of the subsystems also slows down. To sum up, when the cooperation willingness of different subsystems is different, the subsystem with high cooperation willingness evolves quickly, and it also promotes the evolution of the subsystems with low cooperation willingness.

5. Conclusions

Based on the simulation results, we can draw the following conclusions. Firstly, the evolution of each technology management subsystem is affected by the knowledge growth rate of its own, and it is also affected by the coupling and synergy of other subsystems. Secondly, the influence of the subsystem's knowledge growth rate on the evolution of the subsystem is mainly manifested in the evolution speed. Thirdly, the influence of the coupling and synergy on the evolution of the subsystem is also manifested in the evolution speed, and the coupling and synergy can promote the evolution speed more than the knowledge growth rate of the subsystem itself.

Based on these research results, this paper advances the literature in several ways. Firstly, by combining the self-organization theory and the knowledge ecology perspective, this paper develops a conceptually model to describe how technology management system evolves. This paper thus is an attempt to integrate multiple theories for conceptualizing technology management system, offering new directions for technology management research. Secondly, this paper examines the evolution of technology management system based on the self-organization theory, which is in line with the dynamic characteristic of technology management system. Therefore, this paper demonstrates that the evolution of technology management system is more multifaceted than previously assumed.

This paper also has some practical implications. The results indicate that the coupling and synergy between subsystems have significant impact on the evolution of technology management system. Therefore, firms should pay particular attention to the development of the coupling and synergy relationship between technology management subsystems. There are several practices that firms can employ. For instance, firms can provide support for the formal and informal interpersonal communication between different technology management subsystems. Firms can also create a platform for knowledge sharing between different technology management subsystems.

Although this paper provides some relevant contributions to the existing literature, it also suffers some inherent limitations, which leave room for future research. Firstly, this paper only analyze the impact of the knowledge growth rate and cooperation willingness on the evolution of technology management system. However, there may be other influence factors, which need to be investigated. Secondly, in order to simplify the simulation, we set the decreasing rate of knowledge as a constant. However, the decreasing rate of knowledge in different technology management subsystems may be different. For the sake of getting more accurate results, future research is needed to examine the impact of the changing of the decreasing rate of knowledge. Thirdly, this paper does not use a case study method to verify the results. Future research can improve our research by using the case study to examine the results.

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