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Complex adaptive system theory, agent-based modeling, and simulation in dominant technology formation

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Abstract: Dominant technology formation is the key for the high-tech industry to "cross the chasm" and gain an established foothold in the market (and hence disrupt the regime). Therefore, a stimulus-response model is proposed to investigate the dominant technology by exploring its formation process and mechanism. Specifically, based on complex adaptive system theory and the basic stimulus-response model, we use a combination of agent-based modeling and system dynamics modeling to capture the interactions between dominant technology and the socio-technical landscape. The results indicate the following: (i) The dynamic interaction is "stimulus-reaction-selection", which promotes the dominant technology's formation. (ii) The dominant technology's formation can be described as a dynamic process in which the adaptation intensity of technology standards increases continuously until it becomes the leading technology under the dual action of internal and external mechanisms. (iii) The dominant technology's formation in the high-tech industry is influenced by learning ability, the number of adopting users and adaptability. Therein, a "critical scale" of learning ability exists to promote the formation of leading technology: a large number of adopting users can promote the dominant technology's formation by influencing the adaptive response of technology standards to the socio-technical landscape and the choice of technology standards by the socio-technical landscape. There is a minimum threshold and a maximum threshold for the role of adaptability in the dominant technology's formation. (iv) The socio-technical landscape can promote the leading technology's shaping in the high-tech industry, and different elements have different effects. This study promotes research on the formation mechanism of dominant technology in the high-tech industry, presents new perspectives and methods for researchers, and provides essential enlightenment for managers to formulate technology strategies.

Keywords: complex adaptive system theory, agent-based modeling and simulation, dominant technology, socio-technical landscape, adaptation-choice.

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1. Introduction

The high-tech industry's dominant technology refers to the technology that can break the balance of the original technological system in a certain period, which is widely accepted under the interaction of technical possibility and market choice. To a certain extent, the dominant technology determines the main direction of the high-tech industry's technological progress and is the foundation of building the technology system of the high-tech industry [1−4]. The dominant technology has universal acceptance, which means that market followers must follow the generally accepted dominant technology. Therefore, once the dominant technology is formed, it will produce a winner-take-all effect, and the market will reject other technology tracks. Expressly, the core firms of the dominant technology could obtain enormous benefits through a market monopoly. In contrast, other firms that are forced to adopt the dominant technology would lose previously accumulated technical and market advantages. Thus, the dominant technology's formation is key for the high-tech industry to "cross the chasm" and gain an established foothold in the market (and hence disrupt the regime).

However, few related simulation studies consider the dynamic forming process and mechanism of the high-tech industry's dominant technology; in particular, few studies pay attention to the interaction between dominant technology and the socio-technical landscape (ST-landscape). Hence, to ensure and promote the dominant technology's formation, it is of great significance to open the black box of the formation mechanism at the ST-landscape level.

We introduce the complex adaptive system (CAS) theory, multilevel perspective (MLP) theory, agent-based modeling (ABM) and simulation method, and system dynamics model to analyze the dominant technology's formation mechanism at the ST-landscape level. The dynamic interactions between dominant technology and the ST-landscape are tested to explain the dominant technology's forming mechanism.

This study advances dominant technology research on two fronts.

(i) In terms of the research content, compared with previous studies, we consider the complexity and nonlinear interactions in the dominant technology's forming process. Following the solution to the complexity and nonlinear interactions, we introduce the CAS theory, the stimulus-response model proposed by Holland [5], MLP theory and the system dynamics model to simulate the dominant technology's forming process, identifying the characteristics and the changing direction of dominant technology formation. This reveals the interaction principles between the dominant technology and ST-landscape and clarifies the contribution of the interactions between the ST-landscape and the dominant technology to explain the aim of research on dominant technology formation based on the ST-landscape level, which has not been considered in previous investigations. This study enriches the research content of the theory of dominant technology based on MLP theory.

Meanwhile, this study considers the effects of the external selection mechanism (ST-landscape) and the internal behavior mechanism (technology agents) on the dominant technology's formation. In the existing literature, the two kinds of studies develop independently. Most studies focus on the external factors that influence the emergence of dominant technology or discuss the function of the internal behavior mechanism of technology agents and seldom study the internal behavior mechanism of the dominant technology in parallel with the external selection mechanism of the ST-landscape. Therefore, the existing literature cannot analyze a remarkable phenomenon in the dominant technology's forming process when the two mechanisms work together. This study bridges this gap by paying attention to the external selection mechanism's role and analyzes dominant technology agents ' internal behavior mechanisms. It helps researchers understand the effects of ST-landscape on the formation of the dominant technology in the high-tech industry and the associated reasons and mechanisms.

(ii) In terms of the research method, in contrast to the static and traditional methods, we have chosen ABM and simulation, which can identify macro patterns through interactions among various agents at the microlevel; this approach is suitable for complex systems that evolve dynamically over time, and the rationality and advantages of the method are as follows. First, theoretically, ABM and simulation provide new perspectives and ways to solve problems that can address the defects that fail to make part of the principle and phenomenon logical or intuitive. Second, in terms of the method's reliability, ABM and simulation describe and explain the interaction between dominant technology and the ST-landscape. The corresponding conclusions are more reliable. Third, in terms of application, the research method of ABM and simulation has become a meaningful way to study the nonlinearity and complexity of subjects in the field of analyzing technology transformation and technology change [6,7], which are defined and explained via ABM and simulation. With this theory and method, we can provide a complete explanation of the dominant technology forming problems in the high-tech industry from the ST-landscape level to obtain novel conclusions.

Accordingly, this framework sheds light on three questions: (i) How does the dominant technology come about from the ST-landscape level? Are there particular patterns and mechanisms in the formation process? (ii) How do the dominant technology and ST-landscape interact dynamically? What impact does this interaction have on the formation of the dominant technology? (iii) What factors can affect the formation process of the dominant technology at the ST-landscape level?

The remainder of this study is organized as follows. Section 2 reviews the relevant literature. Section 3 presents the theoretical foundation and formation mechanism analysis. Section 4, Section 5 and Section 6 establish the stimulus-response model, agent-based model and system dynamics model of dominant technology formation, respectively. Section 7 provides the simulation results and discussion. Finally, Section 8 concludes and presents the contributions.

2. Literature review

In recent years, with the accelerated evolution of a new round of global scientific and technological revolution, scholars have deepened their research on dominant technologies. The first strand of literature focuses on the definition of leading technology. From a single technical perspective, some scholars argue that a dominant technology refers to a technology that can break the balance of the original technology system in a certain period. It then causes a chain reaction of technological innovation and technological revolution of the high-tech industry and other departments. To a certain extent, the dominant technology determines the main direction of the high-tech industry's technological progress and is the foundation for building the technology system of the high-tech industry [8]. Some scholars define the dominant technology from the perspective of product architecture and believe that the dominant technology has the same meaning as the dominant design; that is, the dominant design is a satisfactory new product widely accepted within a specific time. This new product condenses a single technological innovation and is the product of the common interaction between technology and the market, which represents a design that must be led by innovators who gain market trust and followed by followers [9,10].

Studies in the second research stream focus on the characteristics of the dominant technology, such as leading, dominant, comprehensive[11], advanced technology, mandatory, uncertain, state intervention[12], forward-looking, strategic and catalytic[13].

The third strand of research studies the influencing factors of the dominant technology's formation from different levels, including environmental aspects, such as the institutional environment [14] and market environment [15]; strategic aspects, such as the superiority of the technology, the scale of the installation foundation, the availability of complementary products, the availability of complementary assets, market entry time [16], and the technology initiator's possessiveness strategy [17]; and political, economic and social aspects, for example, government behavior [18] business and political ties [19], financial crisis, and globalization [20].

According to MLP theory, the ST-landscape includes a set of heterogeneous factors, such as oil prices, economic growth, wars, emigration, broad political coalitions, cultural and normative values, and environmental problems. The landscape is an external structure or context for the interactions of actors [21]. Regarding the relationship between dominant technology formation and the ST-landscape, on the one hand, some scholars believe that the ST-landscape provides an influential technology backdrop with ramifications across a variety of regimes and niches: providing gradients and affordances for how to establish socio-technical configurations that serve societal needs [22–24]. On the other hand, novelty spreads over time and eventually may irreversibly transform the sociotechnical landscape [24].

Previous studies have investigated dominant technology [4,10,19,20,25,26]; however, there are some theoretical and methodological defects in the existing literature concerning dominant technology.

(i) In terms of the research content, existing studies on dominant technology are relatively sparse. They are usually limited to the definition from three perspectives: technology, product, and standards and the characteristic, discriminant standards of dominant technology [1,3,4,26–28]. Few studies explore the interaction principles between dominant technology and the ST-landscape in the high-tech industry and the extraordinary influence of interactions on the dominant technology's formation mechanism. However, some studies have explained the evolution of technology toward a dominant design through the product life cycle mode [1,29], which is similar to the formation of the dominant technology, regardless of the different labels used. However, some scholars have emphasized the importance of analyzing how the ST-landscape influences dominant technology based on MLP theory [24,30]. The landscape can make different contributions to the formation of dominant technology. Additionally, the interactions between the ST-landscape and dominant technology may be the key to explaining the essence of the dominant technology's forming mechanism. Few studies identify the dominant technology's forming mechanism and analyze interactions between the ST-landscape and dominant technology based on MLP theory, which makes the existing research on the formation mechanism of dominant technology at the ST-landscape level underdeveloped.

Therefore, on the one hand, the existing literature cannot judge the nonlinear interaction principles between the ST-landscape and dominant technology, as well as the changing trend, which hinders us from opening the black box of the dominant technology's formation mechanism from the ST-landscape level. Moreover, it cannot provide a sufficient theoretical basis for managers to develop strategies to promote the formation of dominant technology. On the other hand, the existing literature does not specify what trends the interaction between dominant technology and the ST-landscape will present when the ST-landscape changes and how these changes affect the formation of dominant technology in the high-tech industry. Therefore, previous studies fail to explain the dominant technology's formation mechanism from both micro internal behavior and macro external influencing perspectives.

(ii) In terms of the research method, most previous studies, oriented by the results, adopt theoretical deduction to analyze variables influencing the dominant technology or the particular characteristics of dominant technology formation. Thus, existing studies use implicit assumptions based on discrete time to analyze the forming problem of a dominant technology. The linear interaction mechanism is adopted to investigate a specific variable's influence on the dominant technology's formation. However, the appearance of the dominant technology is a typical nonlinear dynamic and complex process. The nonlinear interaction between dominant technology and the ST-landscape influences the dominant technology's formation. Hence, the shape and principle of the dominant technology concluded from the traditional linear analytical method may not be so rigorous. The existing literature cannot verify the dynamic interactions and formation process of the dominant technology. The concluded results can only confirm the static works. Therefore, Murmann and Frenken[28] introduced an interdisciplinary approach to studying complex dominant design problems. This approach can help us identify solutions and obtain conclusions that management cannot. However, few studies have adopted interdisciplinary approaches to study the problems of dominant technology formation, and unsolved problems about the complexity principles of dominant technology formation remain.

Therefore, at the ST-landscape level, this paper constructs a stimulus-response model for dominant technology formation in high-tech industries and discusses the formation mechanism of dominant technology from two aspects: the selection of technical standards in the ST-landscape and the response of technical standards to the ST-landscape. Moreover, ABM and system dynamics modeling are comprehensively used to dynamically simulate the dominant technology's shaping model of high-tech industries to compare and analyze the formation process and law of the dominant technology at the ST-landscape level.

3. Theoretical foundation and mechanism analysis

3.1 Theoretical foundation

Holland proposed the CAS theory based on years of research on complex systems, which mainly aimed to study complex systems' complexity and the mechanism of systems' emergence[31]. The basic idea of CAS theory is "adaptability creates complexity". CAS theory holds that the complexity of CAS originates from the adaptability of active agents; that is, the interactions among these agents and the interchange (between agents and the environment) change the agents and the environment. The main characteristic of CAS theory is that it organically links macro and micro aspects. Macroscopically, CAS pays attention to the agent's hierarchy, diversity and aggregation, and emphasizes that the interaction between the agent and the surrounding environment is the system's continuous evolution composed of the agent. Additionally, the influence of random factors affects the system state, the organizational structure and the behavior mode. In the microaspect, CAS focuses on the agent's initiative and adaptability. The agent "learns" or "accumulates experience" through nonlinear interactions with the environment and other agents and remembers the experience in some way according to the learned knowledge to solidify it in its later behavior, change its structure and action to survive better and develop [31].

CAS theory argues that the interactions between agents and the environment follow the stimulus-response model and that the environment changes to stimulate the agent. Under the guidance of goals, the agent adjusts its functional structure and behavioral standards to respond to external environmental changes actively and achieve a state of harmonious coexistence with the environment. The stimulus-response model, proposed by Holland, clarifies the active agent and the agent's interaction to improve the CAS. Stimulus-response models are composed of three parts: detector, IF-THEN rules, and effector. The detector is the agent's organ to receive a stimulus, representing the agent's ability to extract information from the environment. IF-THEN rules are the collection of rules of how the agent responds to a stimulus, which represents the agent's ability to process information. The effector is the organ of an agent to respond, which outputs the agent's response or the performance of the agent's behavior results. The basic principle of this model is that the agent perceives a stimulus from the environment through the detector, matches the detected messages with the IF-THEN rules, finds the matching rules, then activates the effector to generate action to the environment, or activates another matching rule, thus repeating the reaction process of "effector-matching-activation" until the main target of the agent is reached.

3.2 Forming mechanism analysis of dominant technology at the ST-landscape level

At the ST-landscape level, the learning ability, the number of users adopted, and the adaptability have a decisive influence on the formation of dominant technology in the high-tech industry. When the ST-landscape changes, the technology standard's decision-makers with higher learning ability can provide information and knowledge according to the ST-landscape's stimulus received by the detector and then generate actions that can survive from the ST-landscape's choice through the effector, which is adaptive behavior. The above works could promote their technology standards to become the dominant technology. In this process, the leading complexity, high permeability, and comprehensiveness of the high-tech industry's dominant technology bring uncertainty to the ST-landscape. Only with high learning ability and quick response to ST-landscape changes can decision-makers of technology standards win the advantage of selecting the ST-landscape; otherwise, the market will eliminate this technology standard.

Whether a technology standard can be selected in the ST-landscape and eventually form the dominant technology depends on the number of users who adopt it. The number of users will self-reinforce through two mechanisms until the technology standard becomes the dominant technology. The first mechanism is the signal transmission mechanism. When the ST-landscape changes, a technology standard with a higher number of users has a more substantial network effect, which can more quickly perceive the ST-landscape's stimulation. Through communication and cooperation among many technology standard decision-makers, decision-makers can make more favorable judgments on the stimulus and respond to ST-landscape changes. The second mechanism is the complementary effect. The decision-makers of complementary technology are more willing to provide complementary technology for those technology standards with the highest number of users because a higher number of users means that the complementary technology will obtain more potential users. The increase in the number of complementary technology users, in turn, improves the technology standard's number of users, thereby realizing a self-reinforcing scenario. Thanks to the positive feedback effects of the above two mechanisms, the number of adopting users positively impacts dominant technology formation. The higher the number of users is, the higher the possibility of becoming the dominant technology.

The technology standard cannot predict the ST-landscape's choice in advance but perceives the ST-landscape's external stimulation through the detector, makes strategic decisions according to its situation, and then accepts the ST-landscape's test. If the ST-landscape agrees with the technology standard, then the technology standard's adaptability will increase; otherwise, it will decrease. After a long period of natural selection of technology standards by the ST-landscape, the phenomenon of "survival of the fittest" appears in the high-tech industry. The market will eliminate technology standards with lower adaptability. Meanwhile, the technology standards with the highest adaptability will become the dominant technology in the high-tech industry. We can see that higher adaptability is the prerequisite for the formation of dominant technology.

In conclusion, higher learning ability, the number of users, and adaptability can promote the formation of dominant technology by influencing the adaptive behavior of the dominant technology to the ST-landscape and selecting the dominant technology by the ST-landscape.

4. Stimulus-response model for dominant technology formation in the high-tech industry at the ST-landscape level

Based on the stimulation-response model and mechanism analysis, we construct a model for dominant technology formation in the high-tech industry at the ST-landscape level. Considering the interaction characteristics (selection-adaptation) between the technology standard and the ST-landscape, the theoretical model frame diagram is shown in Fig. 1.

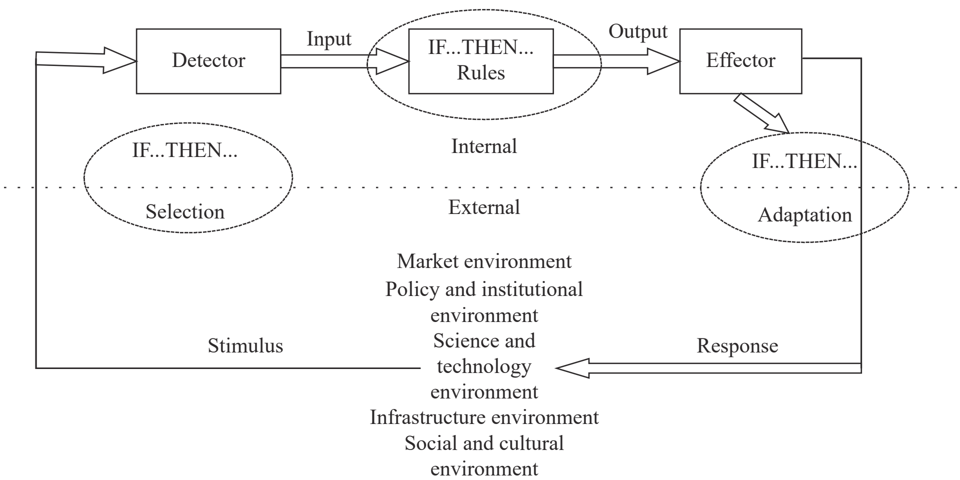


Fig. 1 "Stimulus-response" model of dominant technology formation in high-tech industries

In the stimulus-response model of the high-tech industry dominant technology's formation at the ST-landscape level, each technology standard's adaptive response must be executed from three aspects: a detector, an effector, and a set of IF-THEN rules. Technology standards use the detector to receive the stimulation from the external ST-landscape, that is, the input of relevant information, knowledge, and technology from the market environment, policy and institutional environment, science and technology environment, infrastructure environment, social and cultural environment, etc. IF-THEN rules are the process of how technology standards respond to input ST-landscape stimuli. The effector is the process of adaptive learning in which the decision-maker of the technology standard outputs the response results to the external ST-landscape stimulus.

4.1 Assumptions

This paper introduces the analysis paradigm of CAS theory [5] to describe the formation process of high-tech industry-dominant technology at the ST-landscape level and to provide a theoretical reference for ABM and simulation. We analogize the decision-makers of technology standards with biological individuals, deoxyribo nucleic acid (DNA) with technology standards, and genes with knowledge. DNA carries the necessary genetic information for the synthesis of ribonucleic acid (RNA) and protein, which is an essential biological macromolecule for biological development and normal operation. Biological genes are DNA fragments carrying genetic information, which can determine biological traits. Organisms can transmit genes to the next generation through gene replication and genetic function. Gene replication and inheritance are the transmission and expression of information. Similarly, technology is a living body in the knowledge economy system. Technology gene includes a series of information sets such as knowledge, implementation mode and process flow supporting technology. Just as a biological individual can clone the individual by replicating its DNA, technical genes also have the functions of heredity and replication. Enterprises achieve the goal of replicating the technology with the help of the internal information of a certain technology.

Meanwhile, the dominant technology's formation is the result of the interaction between technology and the ST-landscape in a CAS. Therefore, we propose the following assumptions:

(i) The agent of stimulus-response shows limited rationality and obeys the content of the rules.

(ii) Based on the principle of stimulus-response, the time of the dominant technology's formation in the high-tech industry is discrete, that is, $t = 1, 2, 3, \cdots$.

(iii) The relevant decision-makers in the dominant technology's formation process include technology adopters and technology innovators. In this paper, "decision-makers of technology standards" refer to all decision-makers.

(iv) The decision-makers of technology standards can produce response behavior according to the ST-landscape stimulus analysis result.

(v) Technology decision-maker i holds the technology standard k_i formed by combining knowledge genes.

(vi) Learning ability influences the adaptive response of decision-makers of technology standards and the number of users.

(vii) The learning ability and number of users are affected by changes in the ST-landscape and the current situation of the decision-makers of technology standards (the current adaptive response).

(viii) The adaptability of technology standards is affected by the choice of ST-landscape.

4.2 Interactions between the dominant technology's formation and the ST-landscape

This paper establishes a stimulus-response model for dominant technology formation in the high-tech industry based given the above assumptions and model components. In this model, discrete time leads to different stimulation intensities of the ST-landscape of other nodes and differences in technology standards' knowledge and information. Therefore, we adopt the set to analyze the changes of decision-makers and their technology standards.

The relevant indicators are defined as follows:

$k_i(t)$ is the technology standard of decision-maker i at time t (composed of knowledge genes);

$s(t)$ is information collection (stimulation) of ST-landscape change;

$g(t)$ is the collection of information perceived by the detector;

$r(t)$ is the adaptive responses (effector output) made by decision-makers of technology standards;

$l(t)$ is the learning ability of decision-makers of technology standards;

$n(t)$ is the number of users adopted generated based on the content of rules;

$e_i(t)$ is the adaptation function of a technology standard to the current ST-landscape, $e_i(t) \geqslant 0$.

The number of users adopting $n(t)$ is determined by the selection rules $n_c(t)$ and the adaptation rules $n_a(t)$, expressed as

$$\begin{cases} n(t) = \{n_c(t), n_a(t)\} \\ g(t) \in m(t). \end{cases} \tag{1}$$

According to the principle of stimulus-response, we stipulate that in discrete time t, technology standard decision-makers spontaneously make the adaptive response $r(t)$ to the information $g(t)$ perceived by the stimulus-response model and produce a certain number of adopting users $n(t)$ through the selection of the ST-landscape, which jointly drives the formation of the dominant technology "choice-adaptation". Accordingly, the technology standard updates its knowledge space structure as follows.

$$k_i(t+1) = g(t)l(t)n(t)r(t)k_i(t). \tag{2}$$

Formula (2) means that the technical standard's knowledge updating spatial structure is affected by five factors, including the ST-landscape's change information (perceived by the detector), the learning ability, the number of users, the decision-maker's adaptive response, and the technology standard's current knowledge structure.

(i) "Stimulus" interaction

Considering the adaptation function of technology standards to changes in the ST-landscape, the information set of detector perception is measured by an adaptive function

$$\begin{cases} g(t) = e_i(t)k_i(t) \\ e_i(t) = k_i(t)s(t) \end{cases} \quad (3)$$

where $e_i(t)$ is the adaptability of the current knowledge spatial structure $k_i(t)$ in discrete time t. Adaptability is jointly affected by the current knowledge spatial structure and the information (stimulus) of ST-landscape changes.

(ii) Learning ability

In the process of stimulus response, the decision-makers of technology standards learn according to the changes in the ST-landscape perceived by the detector and update their learning ability, which is represented by

$$l(t+1) = r\{g(t), l(t)\}. \quad (4)$$

Formula (4) shows that learning ability is affected by changes in the ST-landscape and decision-makers' status of technology standards.

(iii) Number of adopting users

The number of adopting users based on the rules' content is constantly updated according to the ST-landscape and technology standard decision-makers status, thereby obtaining

$$n(t+1) = r\{g(t), n(t)\}. \quad (5)$$

(iv) "Response" interaction

The decision-makers of technology standards make adaptive responses based on changes in the ST-landscape, the learning ability of the decision-makers of technology standards, and the number of users, which is represented by

$$r(t+1) = s(t)g(t)l(t)n(t)k_i(t) \quad (6)$$

where $r(t+1)$ is the technology standard decision-maker's adaptive response, indicating that the adaptive response is related to the environmental stimulus, the information perceived by the detector, the decision-makers' learning ability, the number of users, and the technology standard's current knowledge structure.

(v) Adaptability

When the ST-landscape changes, the adaptability's adjustment function is

$$e_i(t+1) = e_i(t)k_i(t)g(t), \quad (7)$$

indicating that the current technology standard's adaptability changes after the ST-landscape selection. The adaptability increases with the ST-landscape's choice; in contrast, the adaptability decreases.

From the above analysis, we can draw some preliminary conclusions: the dominant technology's formation depends on the "stimulus" of the ST-landscape to the technology standard perceived by the detector; it also depends on whether the decision-makers can produce an effective adaptive "response", thereby causing the technology standard system's instability and promoting the dominant technology's formation. Therefore, the learning ability, the number of users, and the adaptability have considerable impacts on whether the ST-landscape can accept technology standards' adaptive response.

5. Simulation design for the stimulus-response model of dominant technology formation

5.1 Reasonable effectiveness of ABM and simulation

The reasons for choosing ABM as the research method are as follows:

(i) In theory, the dominant technology's formation constitutes a complex process, leaving ABM a promising candidate. Moreover, ABM emphasizes the formation of structures rather than their given existence [32], which may provide interesting theoretical insights and offers an opportunity to simulate market behavior for several scenarios in which, for instance, various combinations of measures are used with the aim of boosting a particular technology or preventing another technology from becoming dominant [32].

(ii) In terms of methodology, the case of dominant technology shaping exhibits all six properties described by Rand and Rust as necessary, indicative, and sufficient for using ABM. Specifically, dominant technology meets the medium numbers condition, the existence of local and potentially complex interactions, heterogeneity, rich environment, temporal aspects, and adaptive ability [32,33].

In summary, it is reasonable to use ABM to study the formation of dominant technology in high-tech industries.

The reasons for choosing NetLogo as the software to simulate ABM are as follows: on the one hand, the simulation subject design of NetLogo software meets the fact that the dominant technology of the high-tech industry has the characteristics of the agent; on the other hand, some modules in NetLogo software can supplement and improve the multilayer structure principle model based on "stimulus response", which is expected to obtain valuable discoveries while overcoming the possible defects of system theory and mechanism theory. Therefore, this paper uses NetLogo software to simulate the stimulus-response model of dominant technology formation, including three components: agent, environment, and rules.

5.2 Agent

In this paper, an agent is a technology standard composed of knowledge genes. A series of technology standard decision-makers in the theoretical model is expressed and realized via programming language. We assume that there are ten technology standards in the simulation world. The model describes the agent in terms of attributes and behaviors.

5.2.1 Attributes of the agent

(i) Knowledge spatial structure attributes of technical standards capacity-ability-expertise (CAE)

Based on the viewpoint of CAE [34], this paper establishes the technology knowledge space of high-tech industries (see Fig. 2) to represent the possible knowledge state of all dominant technologies. Therein, CAE comes from the simulating knowledge dynamics in innovation networks (SKIN) model constructed by Gilbert [34]. The model defines the kene as a "gene of knowledge", including some "units of knowledge", and each kene is composed of three parts: C, A and E. C represents a qualification in science, technology or business fields (such as the new energy vehicle manufacturing industry); A is a specific capability in this field (such as battery technology in the new energy vehicle manufacturing industry); E represents the professional level that the subject can achieve using this ability and the adaptability of technological innovation knowledge in the market. A kene is a set of <CAE>. As shown in Fig. 2, the technical knowledge space of the high-tech industry covers all known or learnable kenes, which constitute the technologies in the industry.

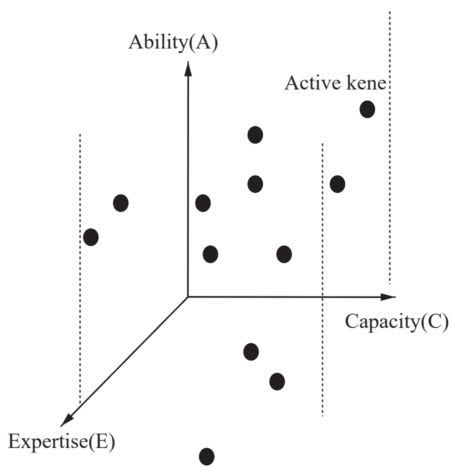


Fig. 2 Dominant technology formation's static technological space model in the high-tech industry

Therefore, we set the technology standard as three-dimensional vectors: capacity, ability, and adaptability. Capacity and ability have the same meaning as above. Furthermore, adaptability (E) represents the technology's market share. In addition, all technology standards are set at the center of the simulation space to observe the spatial position change of agents; that is, we set capacity, ability, and adaptability as random values in the ranges of (35, 65), (35, 65), and (0, 100), respectively.

(ii) Technology agent's learning ability

The learning ability of technology at a certain time is calculated by (4).

(iii) The technology agent's adaptability is calculated by (7).

(iv) The number of users adopted by the technology agent is calculated by (5).

5.2.2 Behavior of the agent

(i) Response behavior

Each agent perceives the change information of the ST-landscape at time t and uses its own learning ability to learn and make adaptive responses, which can be achieved according to (6).

(ii) Natural selection

Considering that the dominant technology of high-tech industries is leading and dominant, the market in which it is located has a high elimination rate. In this paper, the agent with the lowest adaptability (E) is eliminated, and the elimination ratio is $\mu(\mu = 10\%)$.

(iii) Variation

The market in which the leading technology of high-tech industries is located is highly uncertain and dynamic. According to the mutation rate $\sigma = 10\%$, the new generation of agents transforms their genes into other kinds of genes. In this way, a new generation of agents is formed.

Some key codes about agents are set as follows:

```
"
knees-own
[
C-value
A-value
E-value
actural-E
initial-xcor
initial-ycor
initial-E-value
 ]
to go
change-environments
```

```
move-knees
reset-knees-size-and-actural-E
knee-influence-envi
eliminate-knees
update-knees
tick
end
”
```

5.3 Environment

In this paper, the model’s simulation environment, namely, the world in NetLogo, is defined as the ST-landscape, with a wide range of external technical environments. Meanwhile, for the convenience of observation, we set the simulation world as a two-dimensional view: the horizontal axis is the technology standard’s capacity, the vertical axis is the ability of the technology standard, and the size of the world is 100×100. The principle of stimulus-response is to control and describe how technology standards interact with the ST-landscape. Therefore, the variable relations of (1)−(7) are converted into the logic oriented graphic oriented (LOGO) language to design the environment, and each simulation step is set as one unit of time.

5.4 Rules of interaction between the dominant technology and ST-landscape

We set the rules of interaction between the dominant technology and ST-landscape as follows:

(i) Adaptation rules

IF the market environment changes, THEN the technology standard’s learning ability will change;

IF the policy and institutional environment changes, THEN the technology standards’ learning ability will change;

IF the technology environment changes, THEN the technology standard’s learning ability will change;

IF the infrastructure environment changes, THEN the technology standard’s learning ability will change;

IF the social and cultural environment changes, THEN the technology standard’s learning ability will change;

IF the market environment changes, THEN the technology standard’s capacity will change;

IF the policy and institutional environment changes, THEN the technology standard’s capacity will change;

IF the technology environment changes, THEN the technology standard’s capacity will change;

IF the infrastructure environment changes, THEN the technology standard’s capacity will change;

IF the social and cultural environment changes, THEN the technology standard’s capacity will change;

IF the market environment changes, THEN the technology standard’s ability will change;

IF the policy and institutional environment changes, THEN the technology standard’s ability will change;

IF the technology environment changes, THEN the technology standard’s ability will change;

IF the infrastructure environment changes, THEN the technology standard’s ability will change;

IF the social and cultural environment changes, THEN the technology standard’s ability will change.

(ii) Choose rules

IF the response direction of a technology standard is consistent with the change direction of the ST-landscape, THEN the adaptability of the technology standard (E) increases by 1 unit;

IF the response direction of a technology standard is inconsistent with the change direction of the ST-landscape, THEN the adaptability of the technology standard (E) is reduced by 1 unit;

IF a technology standard remains unchanged in the face of ST-landscape changes, THEN the adaptability of the technology standard (E) decreases by 1 unit;

IF the reaction direction of the technology standard is consistent with the change direction of the ST-landscape, THEN the number of users adopted increases by 1 unit;

IF the reaction direction of the technical standards is inconsistent with the change direction of the ST-landscape, THEN the number of users adopted decreases by 1 unit;

IF a technology standard remains unchanged in the face of ST-landscape changes, THEN the number of users adopted remains unchanged.

Notably, all elements of the ST-landscape in the rules set by the model can change direction randomly; that is, the change value can be positive or negative, which, respectively, represent a positive or negative change in the ST-landscape. However, positive or negative changes in the ST-landscape represent only a certain stimulus direction. Accordingly, technical standards can be randomly changed positively or negatively or remain unchanged, symbolizing the response of technical standards. In addition, consistent with the agent setting above, the technical standard attribute capability (C) in this model represents a qualification in the field of science, technology or business. Moreover, the technical standard ability (A) is a specific capability in this field.

6. Construction of the system dynamics model for dominant technology formation

6.1 Reasonable effectiveness of the system dynamics model

System dynamics holds that a system is an organic combination of different and interacting elements and has a certain function. From this perspective, as an advanced manner of dominant technology, the dominant technology system aims to realize a specific function. It is composed of two parts: the technical standard system formed by the logical combination of standard contents within a certain range and the influencing factors involved in the development of technical standards. A technical standard system is a complete organism with high dynamic complexity achieved through the close correlation and interaction between the elements of each part of the system. System dynamics modeling based on evolution emphasizes the multistage, multiloop, nonlinear and dynamic characteristics of the feedback system. It is an effective means to understand the structure and behavior of complex time-varying systems. Its advantages are as follows. First, based on the feedback loop, it can construct a structural model to describe the causal relationship between the elements in a system to intuitively reflect the variable relationships of the real system. Second, it can not only retain the human knowledge and experience of the real process but also realize the repeated operation of the computer in the simulation process. By revealing various system dynamic behaviors after different policy changes, it can obtain rich information to make more meaningful decisions to improve the real situation [35]. Therefore, it is feasible to use the system dynamics method to construct a simulation model of the dominant technology's formation in high-tech industries to gain insight into the dynamic relationship between technological standards and the influencing factors at the ST-landscape level.

6.2 Model building

Based on system dynamics, this paper integrates ST-landscape theory and technology formation theory and reconstructs their internal relationships and related mechanisms. The model presents the interaction between the ST-landscape and the dominant technology of the high-tech industry and the dominant technology's formation process. This model contains six dynamic subsystems: market environment subsystem, social and cultural environment subsystem, policy and institutional environment subsystem, infrastructure environment subsystem, technology environment subsystem and technology standard subsystem. Their causal relationship diagrams are shown in Figs. 3–8.

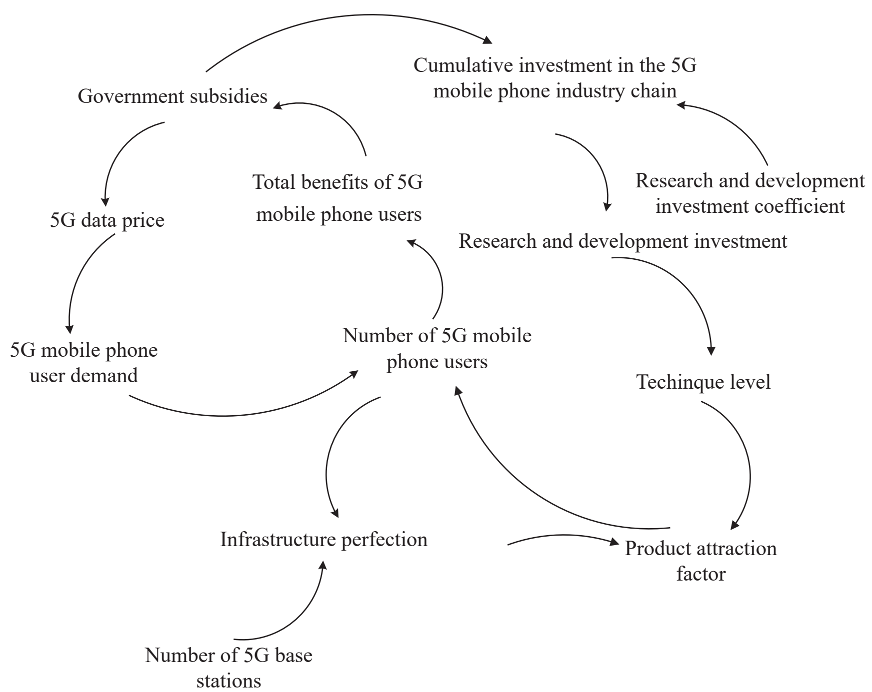


Fig. 3 Causal relationship diagram of the market environment subsystem

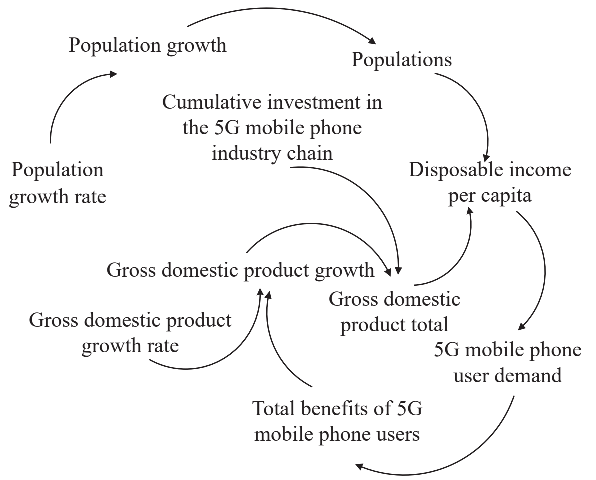


Fig. 4 Causal relationship diagram of the social and cultural environment subsystem

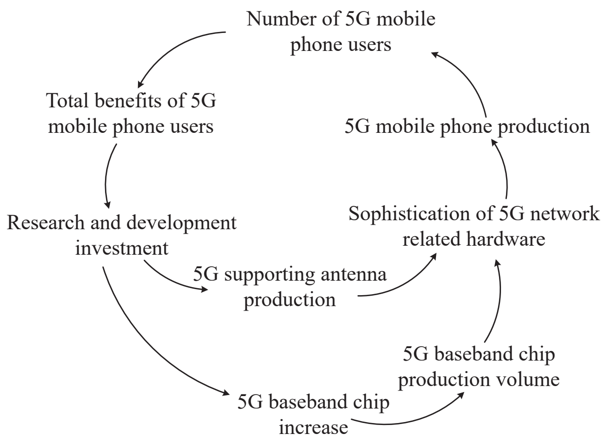


Fig. 7 Causal relationship diagram of the technology environment subsystem

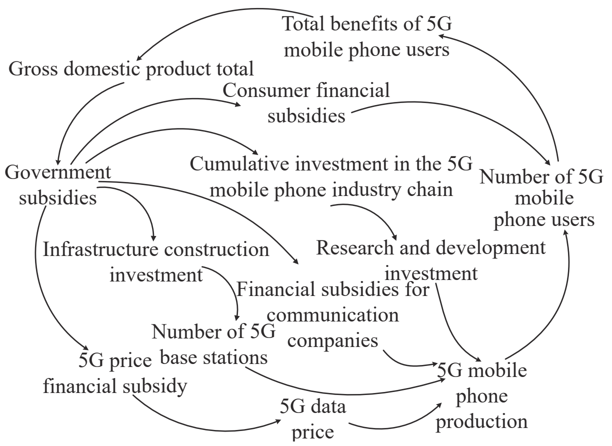


Fig. 5 Causal relationship diagram of the policy and institutional environment subsystem

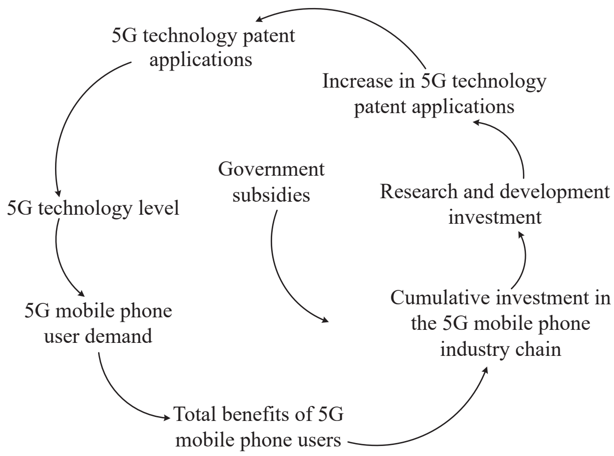


Fig. 8 Causal relationship diagram of the technology standard subsystem

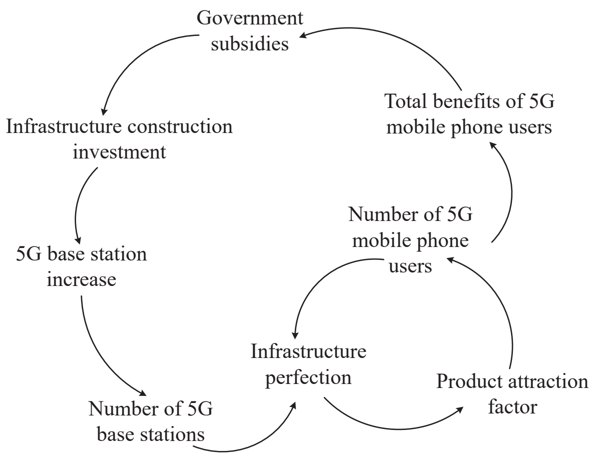


Fig. 6 Causal relationship diagram of the infrastructure environment subsystem

According to the causal relationship diagrams of subsystems, this paper clarifies the quantitative relationship between variables in the system with the equations, calculates the equation coefficients, and sets the main equations of variable relationships, as shown in Table 1. According to the different properties of the variables, the system variables are defined as level variables, rate variables, and auxiliary variables. The level variables describe the cumulative effect of the system; the rate variables reflect the speed of the change of the cumulative effect in the system, that is, with the passage of time, the value of a level variable increases or decreases. As intermediate variables, auxiliary variables play the role of information transfer and conversion between level variables and rate variables.

Table 1 Main equations of variable relationships

Number	Equation	Unit	Category
1	Number of 5G mobile phone users = INTEG (new increment of 5G mobile phone users, the initial number of 5G mobile phone users)	Ten thousand	Level variable
2	New increment of 5G mobile phone users= annual output of 5G mobile phone users × consumption intention of 5G mobile phone users	10 000/year	Rate variable
3	Consumption intention of 5G mobile phone users = price influence of 5G traffic + word-of-mouth influence + advertising influence + price influence of 5G mobile phone users	Dmnl	Auxiliary variable
4	Total benefit of 5G mobile phone users = (purchase price-production cost) × the number of 5G mobile phone users	Ten thousand yuan	Auxiliary variable
5	Cumulative investment in the 5G mobile phone user industry chain = INTEG (total benefit of 5G mobile phone users × production reinvestment coefficient of manufacturer's profit + government subsidies × distribution coefficient of manufacturer's financial subsidy, cumulative investment in the initial 5G mobile phone user industry chain)	Ten thousand yuan	Level variable
6	Research and development investment = cumulative investment in the 5G mobile phone user industry chain × research and development investment coefficient	Ten thousand yuan	Auxiliary variable
7	Technology level = research and development investment/research and development investment transformation	Individual	Auxiliary variable
8	Infrastructure perfection coefficient = number of 5G mobile phone users/number of 5G base stations	Individual	Auxiliary variable
9	Per capita disposable income = gross domestic product/populations	10 000 yuan/person	Auxiliary variable
10	Total gross domestic product = INTEG (gross domestic product growth, initial gross domestic product)	One hundred million yuan	Level variable
11	Gross domestic product growth = total gross domestic product × annual gross domestic product growth rate	Ten thousand yuan	Rate variable
12	Annual gross domestic product growth rate	Dmnl	Constant
13	Total population = INTEG (population growth, initial population)	100 million people	Level variable
14	Population growth = total population × annual population growth rate	Ten thousand people	Rate variable
15	Annual population growth rate	Dmnl	Constant
16	Number of 5G base stations= INTEG (growth of 5G base stations, number of initial 5G base stations)	Individual	Level variable
17	5G base station increase = infrastructure construction investment × investment conversion	10 000 yuan / piece	Rate variable
18	Infrastructure improvement coefficient = number of 5G base stations/number of 5G mobile phone users	Dmnl	Auxiliary variable
19	Product attraction factor = technology level + infrastructure perfection	Dmnl	Auxiliary variable
20	Purchase price = unit production cost × (1 + supply chain profit margin)-government subsidy × consumer financial subsidy distribution coefficient	Ten thousand yuan	Auxiliary variable
21	Supply chain profit margin	Dmnl	Constant
22	Purchase subsidy	Dmnl	Constant
23	5G data price reduction value =5G data price reduction rate ×5G data price	Ten thousand yuan/year	Rate variable
24	5G data price = INTEG (5G data price reduction value, 5G data price)	Ten thousand yuan	Level variable
25	Distribution coefficient of manufacturer's financial subsidy	Dmnl	Table functions
26	5G data price reduction rate	Dmnl	Table functions
27	Government subsidy = INTEG (increase rate of government subsidy, government subsidy)	Ten thousand yuan	Level variable
28	Distribution coefficient of consumer financial subsidies	Dmnl	Table functions
29	Increase rate of government subsidies = government subsidies × growth coefficient of government subsidies	Ten thousand yuan/year	Rate variable
30	Government subsidies or preferential policies	Dmnl	Table functions
31	5G data price impact	Dmnl	Table functions
32	Annual output of 5G mobile phone = production input / unit production cost	Individual	Auxiliary variable

Continued

Number	Equation	Unit	Category
33	Production investment = cumulative investment in 5G mobile phone industrialization × proportion of capital investment for production	Ten thousand yuan	Auxiliary variable
34	5G technology patent application = INTEGER (5G technology patent increase, 5G technology patent application)	Individual	Level variable
35	Increase in 5G technology patents = research and development investment × investment conversion rate + technology level	Per/year	Rate variable
36	5G baseband chip production = INTEG (5G baseband chip added value, 5G baseband chip production)	Ten thousand	Level variable
37	Added value of 5G baseband chip = accumulated investment in 5G mobile phone industrialization × proportion of investment in research and development and production of chip	Ten thousand/year	Rate variable
38	Degree of perfection of 5G network related hardware = 1 / (production of 5G supporting antenna + production of 5G baseband chip)	Dmnl	Auxiliary variable

Based on the causal relationship diagrams of subsystems, this paper uses AnyLogic software to build the system dynamic model of the dominant technology's formation in high-tech industries at the ST-landscape level, as shown in Fig. 9.

Fig. 9 System dynamics model diagram of the high-tech industries' dominant technology's formation

7. Simulation results and discussion

For comparative analysis, the study uses the combination of ABM and simulation (ABMS) and system dynamics to analyze dominant technology formation and its interaction with the ST-landscape. This paper aims to answer the following three questions: (i) How does the dominant technology come about at the ST-landscape level? Are there particular patterns and mechanisms in the formation process? (ii) How do the dominant technology and ST-landscape interact dynamically? What impact does this interaction have on the formation of the dominant technology? (iii) What factors affect the formation process of the dominant technology at the ST-landscape level?

7.1 Simulation results of the ABM of dominant technology formation

We examine the technology standards' dynamic changes when the ST-landscape elements change (market environment, policy and institutional environment, science and technology environment, infrastructure environment, social and cultural environment) to explore the dominant technology's formation process and rules based on the stimulus-response model and ABMS. The simulation results are as follows.

7.1.1 Settings of the initial parameters of the ABMs

We assume that ten technology standards are randomly distributed in the simulation space and are stable in the initial state (tick=0). We ignore the interaction between the technology standards and consider only the interaction between technology standards and the ST-landscape. The architecture of the ABMS is shown in Fig. 10.

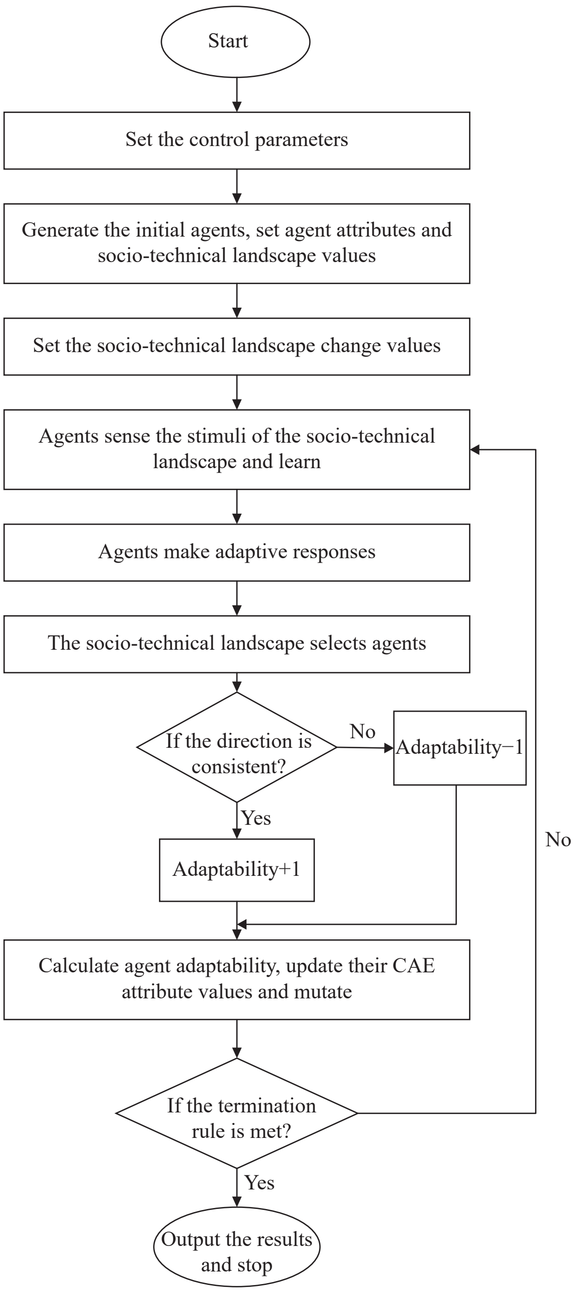


Fig. 10 Architecture of the ABMS

The simulation interface's horizontal axis is the technology standard's capacity value, the vertical axis is the technology standard's ability value, and the circle area's size represents the adaptability value. C represents a qualification in science, technology or business (such as the new energy vehicle manufacturing industry); A is a specific capability in this field (such as battery technology in the new energy vehicle manufacturing industry). The simulation view takes the center point as the origin, and the right direction and the upward direction represent positive changes in attributes and capabilities, respectively. Moreover, the blue circles represent the technology standards set at the center of the ST-landscape space to facilitate observation. There is no ST-landscape change in the initial state, and the simulation of tick 0 is shown in Fig. 11.

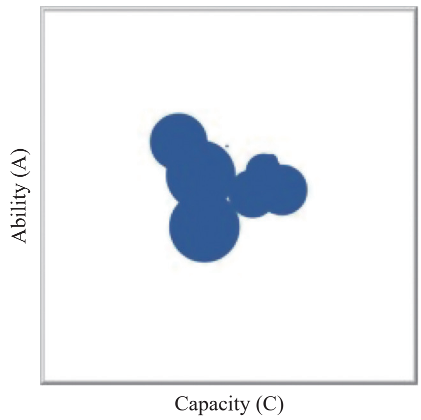
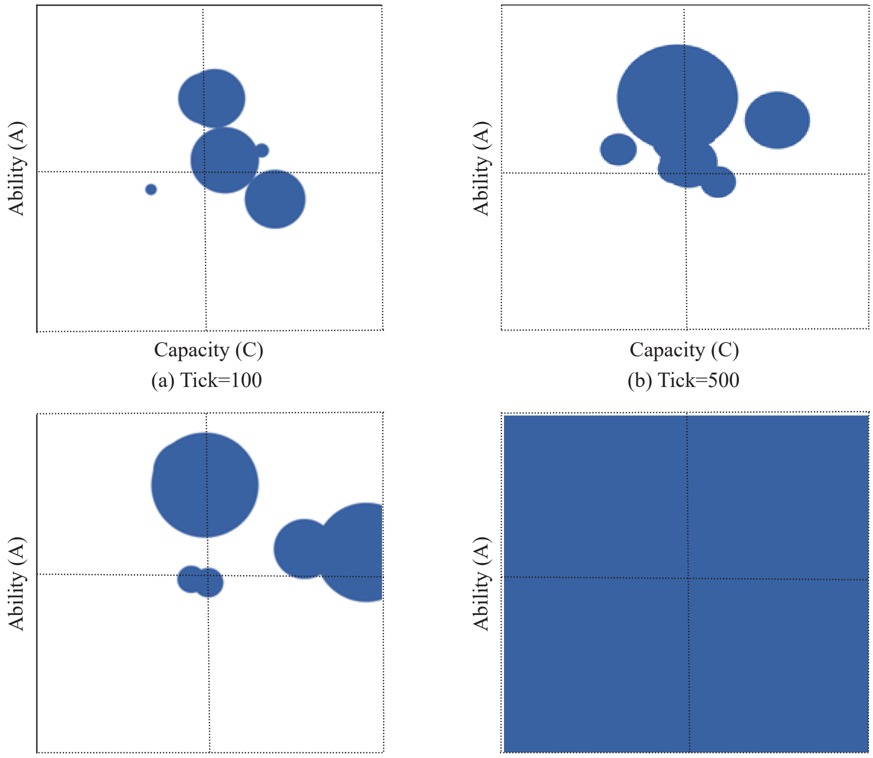


Fig. 11 Initial simulation result of tick 0

7.1.2 Simulation analysis of dominant technology formation when the ST-landscape positively changes based on ABM

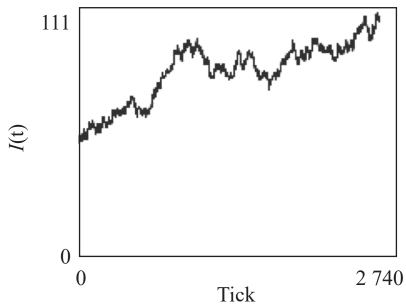
As shown in Fig. 12, the change values of the market environment, policy and institutional environment, science and technology environment, infrastructure environment, and social and cultural environment are all set as "+1 ", which indicates that all ST-landscape elements have positive changes. After the simulation process begins, the spatial distribution of technology standards, the changes in learning ability, the number of users adopted, and adaptability are shown in Fig. 12 and Fig. 13. This paper analyzes the changes in technology standards in every tick in Fig. 12 from the three dimensions of technology standards.



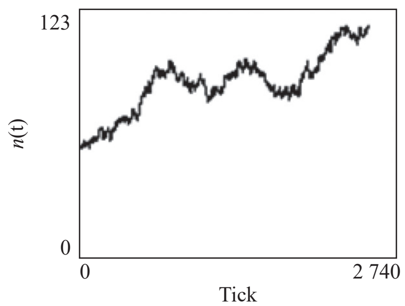
(a) Tick=100 (b) Tick=500

(c) Tick=1 000 (d) Tick=2 600

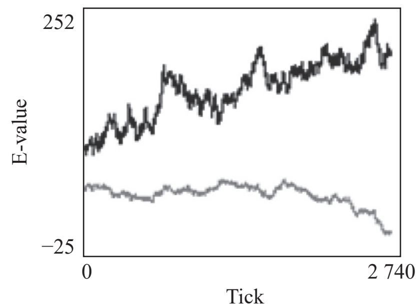
Fig. 12 Technology standards' changes in the formation process of the dominant technology in the high-tech industry at the ST-landscape level at different ticks



(a) Changes in the learning ability over 2 600 ticks under positive changes in the ST-landscape



(b) Changes in the number of users over 2 600 ticks under positive changes in the ST-landscape



(c) Changes in adaptability over 2 600 ticks under positive changes in the ST-landscape

■: max-e; ■: mean-e.

Fig. 13 Changes in different variables over 2 600 ticks under positive changes in the ST-landscape

The spatial distributions of technology standards in Fig. 12(a)−Fig. 12(d) are different compared with those in Fig. 13, in which technology standards are in the center of the initial simulation space interface, indicating that the changes in ST-landscape lead to changes in the technology standards' capacity and ability.

We conduct some further analysis. First, when the ST-landscape positively changes, the technology standards randomly change their space position at tick 100, as shown in Fig. 12(a). This suggests that in the initial stage of the ST-landscape's positive change, the change directions of the technology standards' capacity and ability are random (up, down, and without adaptation). The reason is that some technology standards are susceptible to the stimulation of the ST-landscape. They adjust their capacity (right side of the abscissa) and ability (above the ordinate) toward the positive direction, consistent with the change direction of the ST-landscape (positive), represented by the blue circles moving up and right in Fig. 12(a). In contrast, some technology standards are also sensitive to the ST-landscape but fail to correct the ST-landscape change direction. Their capacity and ability change toward the negative direction, such as the blue circles moving down and left in Fig. 12(a). However, the other part of the technology standards maintains the original capacity and ability level when facing the changed ST-landscape, similar to the blue circle whose position does not change in Fig. 12(a).

Second, in Fig. 12(b), the largest circle is located on the top of the simulation interface at tick 500. This is because the technology standard's decision-makers perceive the ST-landscape's stimulation opportunities and threats in the dominant technology's formation process. They actively join the "adaptation" process with a strong self-learning ability, leading to nonlinear interactions between technology standards and the ST-landscape. Under the promoting effect of learning ability and adaptability, the most significant technology standards continue to follow the current selection direction and become the dominant technology.

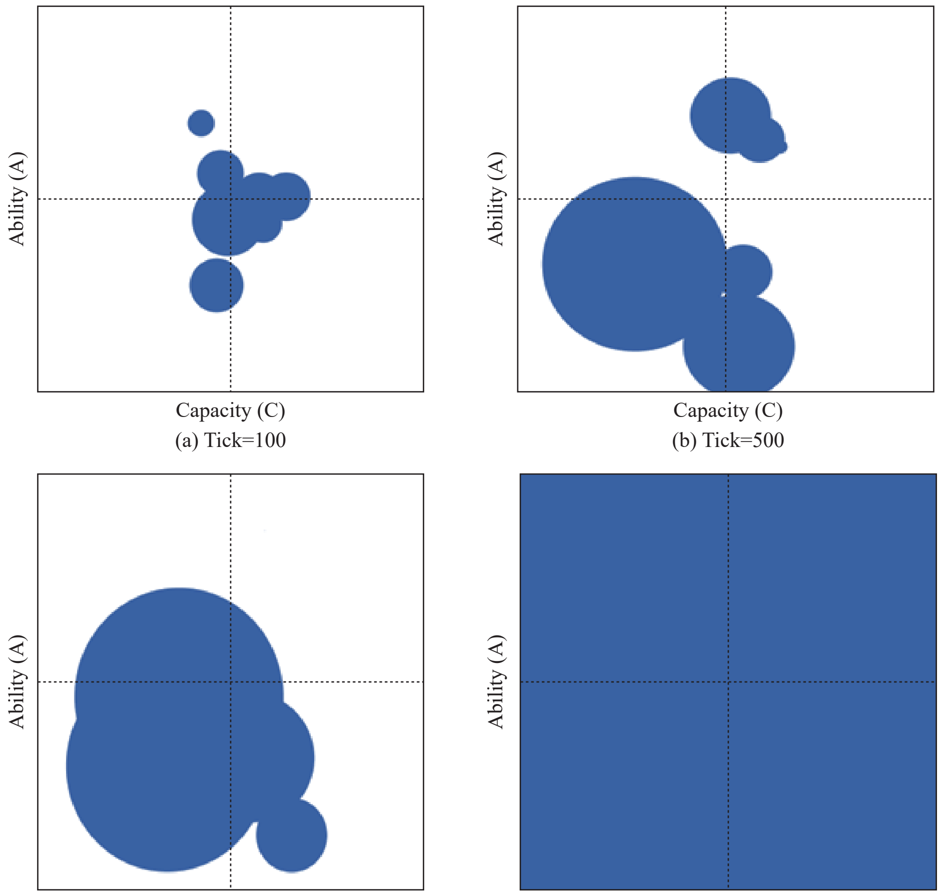
Third, from Fig. 12(c), we can see that at tick 1 000, the technology standards are concentrated in the upper right of the simulation view, indicating that after learning and adjustment, most of the technology standards have made adaptive actions consistent with the change direction of the ST-landscape. This phenomenon reveals the technology standards' spontaneous demand and motivation to pursue higher adaptability. It also shows that the decision-makers' perception and prediction of the ST-landscape and directional adaptive actions can promote the dominant technology's formation in a more orderly manner, suggesting that the dominant technology's appearance is not entirely random. Meanwhile, in Fig. 12(c), the blue circle sizes are different, and there are gaps among them, suggesting that there are gaps among the technology standards' adaptability. This is due to differences in the learning ability of different technology standards. Accordingly, in the interaction process between the technology standard and ST-landscape, the gaps between the technology standards' adaptabilities may further enlarge. Some technology standards with solid learning ability could go through a series of ST-landscape tests, complete the trial and error of "adaptive response", and improve their adaptabilities. In contrast, other technology standards with weak learning ability may be lost in the selection process of "adaptive response", leading to a reduction in their adaptabilities, and they may even be eliminated in the selection process of the ST-landscape. Correspondingly, an increase in adaptability gaps makes the threshold effect in transforming technology standards into dominant technology noticeable. Some technology standards with higher adaptability may directly affect the direction of the dominant technology.

Finally, as shown in Fig. 12(d), the simulation interface becomes all blue, which reveals that under the stimulation of the ST-landscape, a particular technology standard has become the dominant technology by learning and adjusting the adaptive response, occupying the whole technological space of the high-tech industry. Thus, the dominant technology of the high-tech industry at the ST-landscape level has been established.

7.1.3 Simulation analysis of dominant technology formation when the ST-landscape negatively changes based on ABM

Notably, every ST-landscape element in the simulation model can change direction randomly, which means the change value can be positive or negative. The positive or negative changes in the social technology landscape represent a specific stimulus direction, and the positive or negative change will not affect the dominant technology's formation. Therefore, regardless of the direction in which the ST-landscape changes, although the simulation results are different, the basic principles remain consistent.

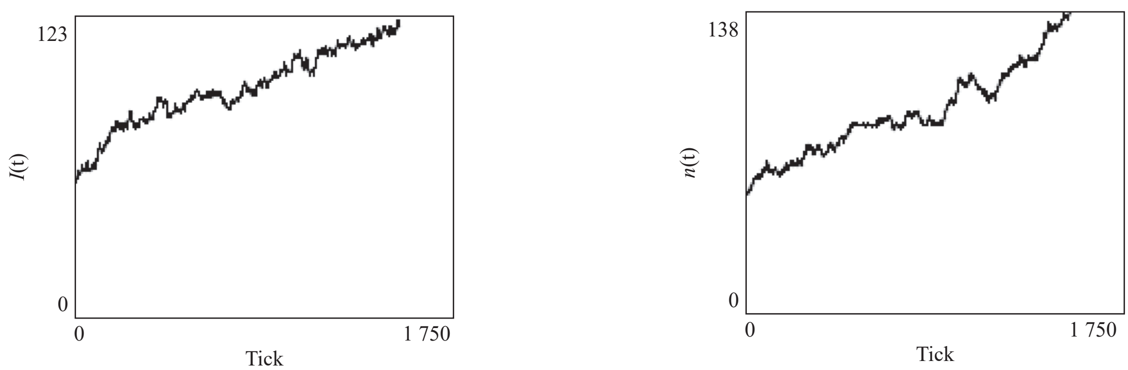
For robustness of the simulation results, this paper sets the change values of the market environment, policy and institutional environment, science and technology environment, infrastructure environment, social and cultural environment as "−1", which indicates that the ST-landscape has a negative change. The spatial location, learning ability, number of users adopted, and adaptability of technology standards change, as illustrated in Fig. 14 and Fig. 15. Fig. 14 shows that, consistent with the negative change in the ST-landscape, technology standards generally change their spatial positions to the left or downward; in Fig. 14(d), consistent with Fig. 12(d), the simulation view is blue. In Fig. 15(c), the adaptability of this technology standard (largest) is increasing: the gap with the average adaptability continues to expand. Thus, the high-tech industry’s dominant technology has been established, and we do not repeat the reasons here. In addition, by observing Fig. 15(a)−Fig. 15(c), we can see that the learning ability curves’ change trends, the number of users adopted, and adaptability are consistent with the results in Fig. 13(a)−Fig. 13(c).



(a) Tick=100 (b) Tick=500

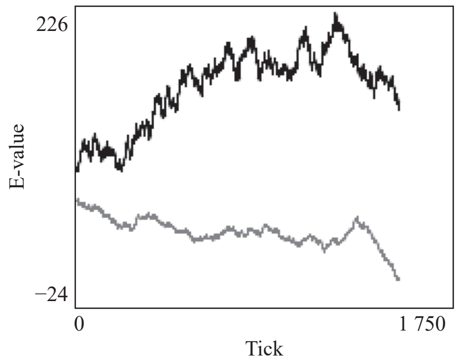
(c) Tick=1 000 (d) Tick=1 500

Fig. 14 Changes in the technology standards in the formation process of the dominant technology in the high-tech industry at the ST-landscape level at different ticks



(a) Changes in the learning ability over 1 500 ticks under negative transitions in the ST-landscape

(b) Changes in the number of users adopted over 1 500 ticks under negative transitions in the ST-landscape



(c) Changes in the adaptability over 1500 ticks under negative transitions in the ST-landscape

■: max-e; ■: mean-e.

Fig. 15 Variable changes over 1 500 ticks under negative transitions in the ST-landscape

7.2 Simulation results of the system dynamic model of dominant technology formation

As the macrolevel influencing environment, the ST-landscape can promote the leading technology's formation, but the role of different ST-landscape factors on the leading technology's formation and whether they can accelerate the formation process of the leading technology must be further discussed. Therefore, this paper simulates the system dynamic model to further analyze the dynamic relationship between the dominant technology's formation and ST-landscape factors.

This paper selects "growth rate of 5G mobile phone users" from the market environment subsystem, "5G data price reduction rate" from the social and cultural environment subsystem, "5G base station growth rate" from the infrastructure environment subsystem, "government subsidy growth coefficient" from the policy and institutional environment subsystem, "5G baseband chip growth rate" from the technology environment subsystem, and "the standard-essential patent applications for 5G technology" from the technology standard subsystem. Furthermore, the simulation in this section is divided into two cases, namely, positive change and negative change in the ST-landscape, to compare with the results of the agent-based simulation.

7.2.1 Simulation analysis of dominant technology formation when the ST-landscape positively changes based on system dynamics

(i) Integrity analysis

When the ST-landscape changes positively, the growth rate of 5G mobile phone users (market environment), the 5G data price reduction rate (social and cultural environment), the 5G base station growth rate (infrastructure environment), the government subsidy growth coefficient (policy and institutional environment), and the 5G baseband chip growth rate (technology environment) all increase by 5%, indicating that all elements of the ST-landscape have changed positively. Thus, the change curve of the standard-essential patent applications for 5G technology is obtained, as shown in Fig. 16. In Fig. 16, the red curve represents the change curve of 5G technology standard-essential patent applications in the initial state, and the blue curve represents the change curve of 5G technology standard-essential patent applications after a 5% positive change in the ST-landscape. As shown in Fig. 16, compared with the initial state, with a value of 5 683.759, 5G technology standard-essential patent applications after a positive change in the ST-landscape significantly increase (to a value of 7 757.697), and the gap between the two gradually widens over time. Therefore, there is a positive correlation between the ST-landscape and dominant technology's formation in high-tech industries.

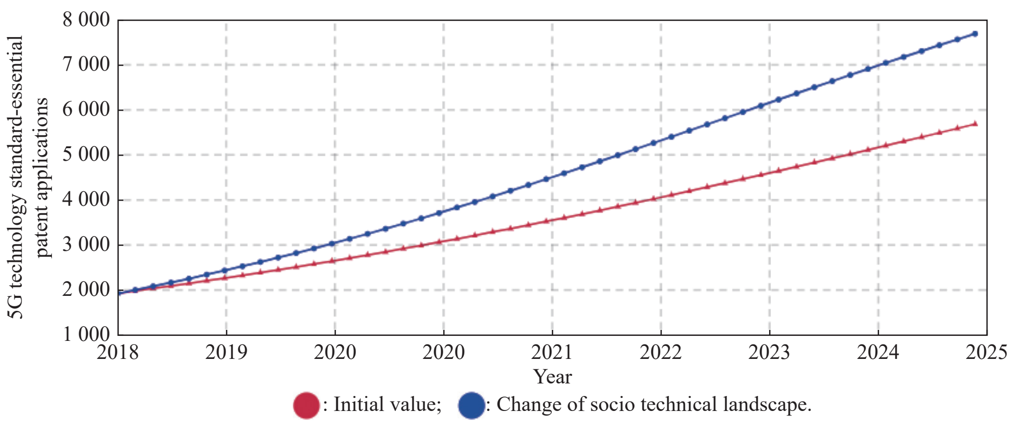


Fig. 16 Change curve of 5G technology standard-essential patent applications when the ST-landscape changes positively

(ii) Sensitivity analysis

Further sensitivity analysis is performed on the system dynamics model. In this paper, the growth rate of 5G mobile phone users (market environment), the 5G data price reduction rate (social and cultural environment), the 5G base station growth rate (infrastructure environment), the government subsidy growth coefficient (policy and institutional environment) and the 5G baseband chip growth rate (technology environment) are set to increase by 5%. Thus, every element of the ST-landscape has undergone a positive change. The curve of the 5G technology standard-essential patent applications given positive changes in different factors can then be obtained, as shown in Fig. 17.

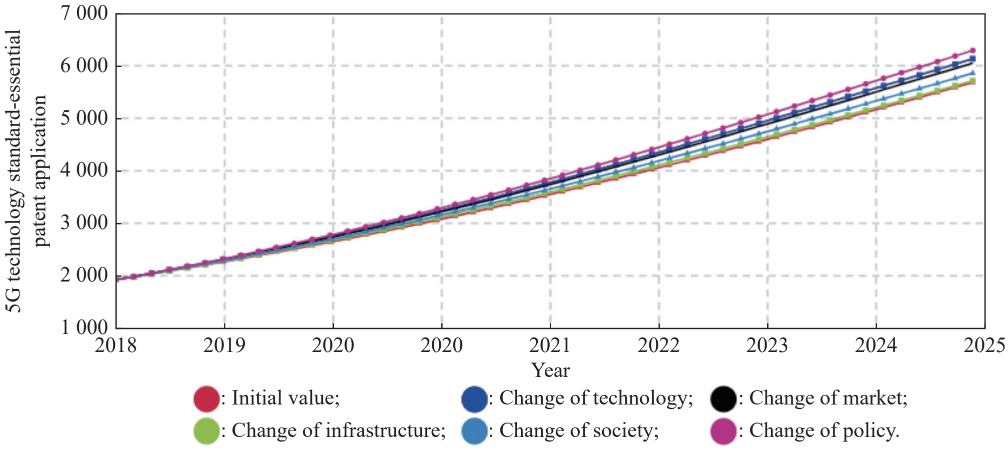


Fig. 17 Curves of 5G technology standard-essential patent applications under positive changes in different factors

According to the simulation results in Fig. 17, increasing the value of technology environment, market environment, infrastructure environment, social and cultural environment, policy and institutional environment by 5%, respectively, increases 5G technology standard-essential patent applications from 5 683.759 to 6 132.089, 6 049.819, 5 713.621, 5 856.844, 6 290.582 respectively in 2025. Different elements of the ST-landscape have different effects on the dominant technology's formation in high-tech industries. Therefore, the policy and institutional environment has the greatest effect on the dominant technology's formation, with a value of 6 290.582, followed by the technology environment, market environment, social and cultural environment, and infrastructure environment.

7.2.2 Simulation analysis of dominant technology formation when the ST-landscape negatively changes based on system dynamics

As mentioned above, the change value of every element of the ST-landscape in the system dynamics model is positive or negative, which, respectively, represents a positive or negative change in the ST-landscape. However, positive or negative changes in the ST-landscape represent only a certain stimulus direction. Regardless of which direction the simulation sets the ST-landscape changes, the principle remains the same despite different results.

In this section, the simulation design is consistent with that in Subsection 7.2.1 to obtain robust simulation results. First, this paper conducts an overall analysis of the model and sets the growth rate of 5G mobile phone users (market environment), the 5G data price reduction rate (social and cultural environment), the 5G base station growth rate (infrastructure environment), the government subsidy growth coefficient (policy and institutional environment) and the 5G baseband chip growth rate (technology environment) all reduced by 5%. Thus, all elements of the ST-landscape have changed negatively. The overall change curve of 5G technology standard-essential patent applications is then obtained when the ST-landscape changes negatively, as shown in Fig. 18. When the ST-landscape is reduced by 5%, 5G technology standard-essential patent applications decrease from 5 683.759 to 4 892.098. Therefore, lowering or increasing the value of the ST-landscape will significantly slow or accelerate the formation process of the dominant technology.

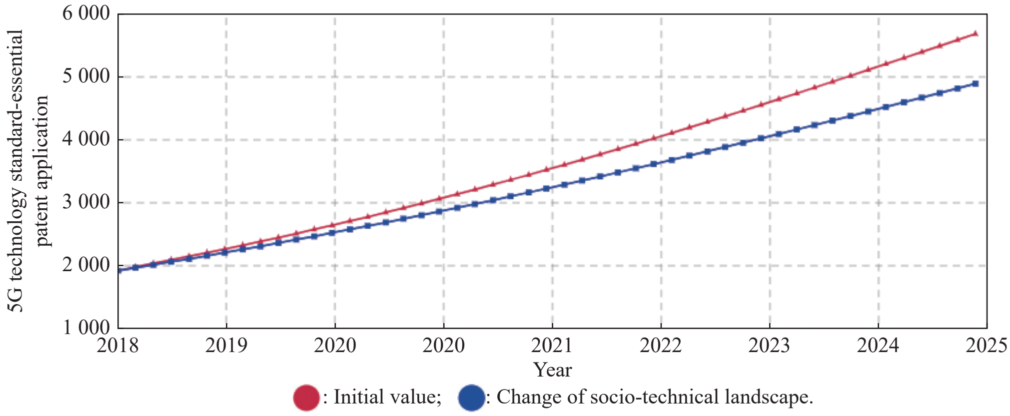


Fig. 18 Change curve of 5G technology standard-essential patent applications when the ST-landscape changes negatively

Second, further sensitivity analysis is performed on the system dynamics model. In this section, the growth rate of 5G mobile phone users (market environment), the 5G data price reduction rate (social and cultural environment), the 5G base station growth rate (infrastructure environment), the government subsidy growth coefficient (policy and institutional environment) and the 5G baseband chip growth rate (technology environment) are set to reduce by 5%, so every element of the ST-landscape has undergone negative changes. Thus, the curve of the 5G technology standard-essential patent applications under the negative change of different factors can be obtained, as shown in Fig. 19. Reducing the value of the technology environment, market environment, infrastructure environment, social and cultural environment, policy and institutional environment by 5% decreases 5G technology standard-essential patent applications from 5 683.759 to 5 547.376, 5 590.926, 5 329.102, 5 162.6, 5 589.51, respectively, in 2025.

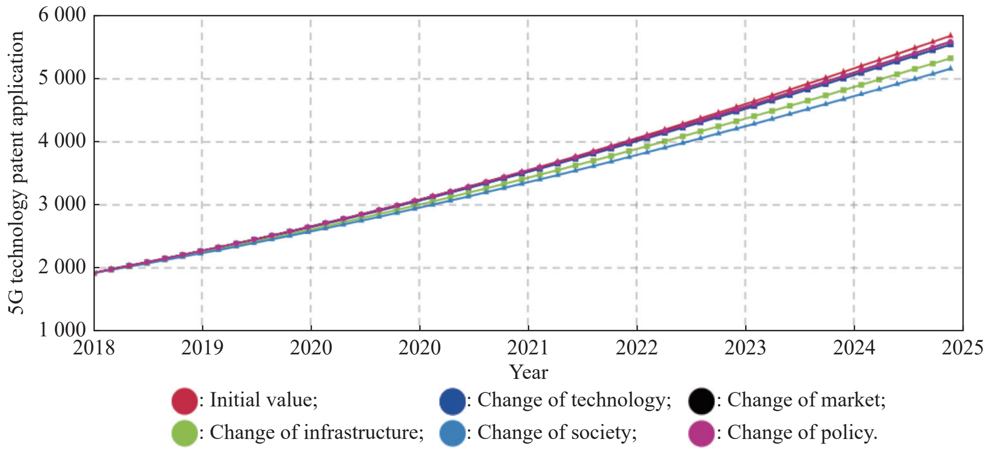


Fig. 19 Curves of 5G technology patent applications under negative changes in different factors

7.3 Discussion

According to the formation mechanism of the dominant technology of the high-tech industry at the ST-landscape level, we further analyze and discuss the simulation results.

7.3.1 Discussion on the formation process of the dominant technology

(i) Simulation analysis of the adaptation process of technology standards to the ST-landscape

From the simulation results in Fig. 12(a)–Fig. 12(c) and Fig. 14(a)–Fig. 14(c), we can see that with the progress of the simulation, almost all technology standards move to the right (left) or up (down), which suggests that most technology standards have sought the correct development direction through the endless selection of technology standards by the ST-landscape and the multi-round responses of technology standards, reflecting the adaptation mechanism of technology standards to the ST-landscape. Specifically, at the end of the first simulation round, the information of the ST-landscape's selection on technology standards (represented by an increase or decrease in the adaptability of technology standards) is obtained by the agents of the technology standards. Because technology standard decision-makers can perceive their adaptability changes, they will keep the original technology developing direction (up) if the adaptability increases. By contrast, they will change the original technology development direction (from down to up) if the adaptability decreases. The technology standards that have no adaptability change realize that the technology standards' development direction should adapt to the ST-landscape. Thus, they begin to adjust their activities. This is the memory process of technology standards for the ST-landscape in the simulation. At tick 1 000, the technology standard's adjustment direction has changed to upward (or downward). The process of oriented technology standard development activities and memory constitute the adaptation dynamic of technology standards to the ST-landscape, verifying that the adaptive response of technology standards to the ST-landscape is vital for the dominant technology's formation.

(ii) Simulation analysis of the selection process of technology standards by the ST-landscape

Taking the positive change in the ST-landscape as an example, by analyzing Fig. 12(a)−Fig. 12(c), we can see that the closer the technology standard is to the right and top of the simulation view, the larger the circle area is. This suggests that the higher the adaptability of the technology standard is, the more able technology standard decision-makers are to judge whether the last round of adaptive response meets the requirements of the change in ST-landscape through the results of selection by the ST-landscape. The reason may be that given the positive direction of the ST-landscape change in the model, it can only accept the positive evolution of the technology standards' response results. In other words, the adaptability of the technology standards whose change direction is up will increase by one unit. In comparison, the adaptability of the technology standards whose change direction is down or not changed will decrease by one unit because the ST-landscape does not accept them. The above simulation results confirm that the selection of technology standards by the ST-landscape plays a crucial role in the dominant technology formation process.

(iii) Simulation analysis of the formation and establishment of the dominant technology

As shown in Fig. 12(d) and Fig. 14(d), at ticks 2 600 and 1 500, the simulation view becomes blue, indicating that a particular technology standard has fully occupied the market in the high-tech industry, which means that this technology standard is in a completely dominant position. Moreover, Fig. 13 (c) shows that the most extensive technology standard's adaptability at the ST-landscape level is rising. In contrast, the average adaptability of all the technology standards has decreased substantially. The gap between them widens, indicating that this technology standard's adaptability advantage remains stable and shows a continuous expansion trend. According to the definition and characteristics of the high-tech industry's dominant technology, this paper infers that the high-tech industry's dominant technology has formed under the above simulation conditions. In other words, a specific technology standard is finally established as the dominant technology of the entire high-tech industry by making the correct adaptive response in time and selection by the social technology landscape.

(iv) Internal and external mechanism analysis

In technological innovation management and MLP theory, the dominant technology's formation mechanism is a long-lasting and valuable research topic. The results reveal that the dominant technology's formation depends on the adaptive response to the ST-landscape and the selection of technology standards by the ST-landscape. The first lens, the external selection mechanism, attaches more importance to the influence of ST-landscape choice on the formation of the dominant technology. The second lens, the internal mechanism, attaches more importance to decision-makers' adaptive behaviors of technology standards. Consideration of both lenses is both theoretically and practically important. The results and implications of each and their possible effects must be examined and incorporated into a framework to understand the formation process and mechanism of the dominant technology.

7.3.2 Discussion on the variables' changes

(i) Learning ability

Fig. 13 (a) shows that the effect of learning ability on the dominant technology's formation lags behind, which reflects a "critical scale" for the promotion of learning ability on the dominant technology's formation. The reason may be that on the one hand, through the interaction with the ST-landscape, technology standards receive external knowledge, technology, and other related information, then process, absorb and transform this information, which takes some time. On the other hand, in the process of capturing ST-landscape information, high-tech industries tend to screen the information within their learning ability, and information with too large of a difference (knowledge distance) is difficult to enter the screening scope of the main body of technical standards, and it is also difficult to capture. Therefore, there is a critical scale and lag between learning ability and the leading technology's formation.

(ii) Number of users adopted

As shown in Fig. 13 (b), overall, the curve of the number of users adopted shows a step-by-step upward trend; that is, it rises in the early stage, fluctuates slightly in the middle stage, and continues to increase in the later stage. In the early and middle stages of the dominant technology formation process, the selection direction of dominant technology by the ST-landscape is not clear. Decision-makers of technology standards can only continuously adjust and make an adaptive response based on experience. The number of users adopted presents a mixed state (rise and fall). In the final stage, the learning ability and adaptability of technology standards increase. The number of users adopted continues to grow under the signal transmission mechanism and complementary mechanism.

(iii) Adaptability

Combined with the simulation results in Fig. 13 (c), we can see that almost all technology standards have found the correct adjustment direction at tick 2 600 of the dominant technology's formation process. However, the adaptability of different technology standards is not the same. Technology standards with high adaptability have more chances to correct their adjustments, and their adaptability will not be significantly affected by the changing ST-landscape. If they adapt in the same direction as the ST-landscape changes, they will achieve higher adaptability. In contrast, technology standards with low adaptability are likely to be eliminated by the ST-landscape before finding the right adjustment direction. In addition, staying in place may lead to a faster exit from the market. This phenomenon confirms Darwin's view of "survival of the fittest". Due to the stimulation of the ST-landscape, the adaptability of the dominant technology presents a fluctuating upward trend.

In terms of adaptability, there is a minimum threshold and a maximum threshold in affecting the leading technology's formation. The minimum threshold is the basic breakthrough point at which adaptability can affect the leading technology's formation, and the maximum threshold means the most likely result of adaptability affecting the formation of dominant technology, which depends on the learning ability of technical standards and needs the support of the ST-landscape. Specifically, in the formation stage of the dominant technology, the innovation activities around dominant technology are highly active, which is an important period for learning ability to give full play to its role and support the development of standards and necessary patents to make key breakthroughs. Of course, without the synchronous "stimulation-selection" of the ST-landscape, even if the adaptability is strong, it cannot accelerate the dominant technology's formation process.

8. Conclusions

8.1 Main conclusions

This paper constructs a complex stimulus-response model of a dominant technology's formation in the high-tech industry at the level of the ST-landscape and discusses the formation mechanism from two aspects: the selection of technology standards by the ST-landscape and the adaptive response of technology standards to the ST-landscape. ABMS and system dynamics are combined to present the dynamic process of dominant technology formation and to comparatively analyze the formation law of dominant technology in the high-tech industry at the level of the ST-landscape. To answer the three questions raised in the introduction section, our main findings and conclusions are as follows:

(i) The driving force for the dominant technology's formation comes from the ST-landscape, which mainly includes the continuous promotion of policy and institutional environment support, the element support of the technological environment, the demand pulling of the market environment, the resource support of the social and cultural environment, and the supplementary coordination of the infrastructure environment. The above factors constitute the dynamic chain of dominant technology formation and promote the whole process of leading technology formation.

(ii) The dominant technology and ST-landscape have a dynamic interactive relationship of "stimulation-response-selection". The ST-landscape provides guidance, focusing on the gradual regulation process and promoting the dominant technology's formation.

(iii) The formation of the dominant technology in the ST-landscape can be described as a complex dynamic process in which the adaptability of technology standards is constantly enhanced until it becomes the dominant technology under the dual effect of internal and external mechanisms. Specifically, under the stimulation of the ST-landscape, the decision makers of technology standards make adaptive responses according to the internal decision-making mechanism that are accepted through the external selection mechanism of the ST-landscape. In this process, the adaptability of technology standards increases until it becomes the dominant technology.

(iv) The dominant technology's formation in the high-tech industry is influenced by learning ability, the number of users adopted and adaptability. There is a critical scale of learning ability to promote the formation of leading technology. A high number of users can promote the dominant technology's formation by influencing the adaptive response of technology standards to the ST-landscape and the choice of technology standard by the ST-landscape. There is a minimum threshold and a maximum threshold for the role of adaptability in the dominant technology's formation.

(v) The ST-landscape can promote the shaping of leading technology in the high-tech industry, and different elements have different effects.

8.2 Contributions

The purpose of our study is to theoretically and methodologically improve our identification and understanding of dominant technology formation. We thereby contribute to the theoretical development and methodological advancement of dominant technology and discuss the results.

8.2.1 Theoretical contributions

This paper makes several theoretical contributions to the related literature.

First, in this research, we introduce a new theory to analyze the dominant technology formation mechanism in the high-tech industry. Based on CAS theory, we attach more importance to the analysis of the interaction mechanism between the ST-landscape and dominant technology. The dominant technology's formation is viewed as an evolutionary process of CAS, and we consider how the ST-landscape and dominant technology interact nonlinearly in the dominant technology's formation process. By identifying the key factors, we can promote the understanding of the black box in the complex adaptive principle of dominant technology formation in the academic field.

Second, taking the ST-landscape stimulus as the external selection mechanism and the adaptive behavior of dominant technology as the internal decision-making mechanism, we study the two mechanisms together and identify different critical factors of internal and external mechanisms. The results underscore, for dominant technology research, the value of juxtaposition for examination rather than merely solely research.

8.2.2 Methodological contributions

This paper also makes some methodological contributions. First, dominant technology formation in high-tech industries is analyzed based on a stimulus-response model and an agent-based model, which overcomes the limitations of traditional simulation methods and realizes the organic combination of individual micro behavior and macro emergence in complex systems. Second, a comparative simulation analysis is conducted using the system dynamics model, emphasizing the multistage, multiloop, nonlinear and dynamic characteristics of the feedback system. By constructing a structural model describing the causal relationship between the internal elements of the system formed by the leading technology, the approach can intuitively reflect the variable relationship of the real system and reveal the real process of dominant technology formation in high-tech industries.

8.3 Limitations and future research

There may be some limitations in the method of the study, including two aspects. First, although the complex adaptive theory of complexity science can explain the high-tech industry's dominant technology formation mechanism from an ST-landscape perspective, some limitations remain. Our research must take metaphor as a prerequisite; namely, we need to take the dominant technology's formation as a CAS and explain the system evolution by analyzing the interaction between the ST-landscape and dominant technology, which compose and affect the structure of the system. These factors may influence specific state variables or impact a nuanced state variable at a particular point in the dominant technology's formation system. This factor is overlooked in our study, which is a deficiency caused by theoretical defects. Second, although we establish the model following the feature identification of the CAS and the order parameter for rigorously designing the evolution of the dominant technology's formation system, the variables that influence the system's development may not notably change with the evolutionary cycle in practice. However, the widely used methods to study CAS, including the approaches we use, cannot fully identify this situation, limiting this method.

Empirical research on the dominant technology's formation mechanism with different practical samples is the present study's primary focus. As the framework we propose can be applied in many fields, we will collect and analyze samples from different subjects, such as "production, learning, and research" systems and practice communities. Detailed theoretical analysis can also guide the practical work and play the role of connecting, to a certain extent, which is meaningful for defining different features of dominant technology formation for further comparative analysis. Meanwhile, we will consider introducing technology diffusion. By improving the existing model, we will provide a full explanation for the formation mechanism of dominant technology from theoretical and practical perspectives to further refine the research.

References

[1] ABERNATHY W J, UTTERBACK J. Patterns of industrial innovation. Technology Review, 1978, 80(7): 40–47.

[2] SUAREZ F F, UTTERBACK J M. Dominant designs and the survival of firms. Strategic Management Journal, 1995, 16(6): 415–430.

[3] CHRISTENSE C M, SUAREZ F, UTTERBACK J M. Strategies for survival in fast-changing industries. Management Science, 1998, 44(12): 207–220.
[4] SUAREZ F F. Battles for technological dominance: an integrative framework. Research Policy, 2004, 33(2): 271–286.
[5] HOLLAND J H. Hidden order: how adaptation builds complexity. New York: Addison Wesley, 1995.
[6] LOPOLITO A, MORONE P, TAYLOR R. Emerging innovation niches: an agent based model. Research Policy, 2013, 42(6/7): 1225–1238.
[7] BERGMAN N, HAXELTINE A, WHITMARSH L. Modelling socio-technical transition patterns and pathways. Journal of Artificial Societies & Social Simulation, 2008, 11(3): 29.
[8] ZHANG F W. The research for the attachment of coal industry’s related technology and leading technology. China Mining Magine, 2010, 19(6): 41–43.
[9] TUSHAMN M L, ANDERSON P. Technological discontinuities and dominant designs. Administrative Science Quarterly, 1990, 35: 604–633.
[10] FERNANDEZ E, VALLE S. Battle for dominant design: a decision-making model. European Research on Management & Business Economics, 2019, 25(2): 72–78.
[11] WU D Y, ZHANG Z J. Dominant design: the new paradigm of market entry barriers. East China Economic Management, 2006, 4: 126–129.
[12] LIU H Y, PENG F Y, WU C S. The formation mechanism and growth path of strategic emerging industries. Science & Technology Progress and Policy, 2012, 29(11): 46−49.
[13] LU J Z. Development direction of agricultural science and technology in China during new era and important proposition analysis. Journal of Agricultural Science and Technology, 2014, 16(6): 1–6.
[14] CHESBROUGH H. Arrested developmen: the experience of European hard disk drive firms in comparison with US and Japanese firms. Evolutionary Economics, 1999, 9: 287–329.
[15] SRINIVASAN R, LILIEN G L, RANGASWAMY A. The emergence of dominant designs. Journal of Marketing, 2006, 70(2): 1–17.
[16] TAN J, XUE H Z. The formation mechanism of dominant design and its contributing strategic factors. Chinese Soft Science, 2007, 7: 41–53.
[17] LI D, LIU W, SONG Z. Appropriablity strategy, technology flexibility and the emergence of dominant designs: a comparative case study. Science & Technology Progress and Policy, 2019, 36(11): 1–8.
[18] MIU X M, ZHAO H. The roles of government in the evolution of dominant design: study based on China ’s telecom industry. Journal of Information, 2008, 11: 155–158.
[19] DAI H, ZENG D, QUALLS J W, et al. Do social ties matter for the emergence of dominant design? The moderating roles of technological turbulence and IRP enforcement. Journal of Engineering and Technology Management, 2018, 47: 96–109.
[20] BREM A, NYLUND P, VIARDOT E. The impact of the 2008 financial crisis on innovation: a dominant design perspective. Journal of Business Research, 2020, 110: 360–369.
[21] GEELS F W. Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case study. Research Policy, 2002, 31(8/9): 1257–1274.
[22] SMITH A, VOSS J P, GRIN J. Innovation studies and sustainability transitions: the allure of the multi-level perspective and its challenges. Research Policy, 2010, 39(4): 435–448.
[23] GEELS F W. Disruption and low-carbon system transformation: Progress and new challenges in socio-technical transitions research and the multi-level perspective. Energy Research & Social Science, 2018, 37: 224–231.
[24] RIP A, KEMP R. Technological change. RAYNER S, MALONE E L, ed. Human choice and climate change. Ohio: Battelle Press, 1998.
[25] HEKKERT M, HOED R V D. Competing technologies and the struggle towards a new dominant design. Greener Management International, 2004, 47(16): 28–43.
[26] ANDERSON P, TUSHMAN M L. Technological discontinuities and dominant designs: a cyclical model of technological change. Administrative Science Quarterly, 1990, 35(4): 604–633.
[27] BREM A, NYLUND A P, SCHUSTER G. Innovation and de facto standardization: the influence of dominant design on innovative performance, radical innovation, and process innovation. Technovation, 2016, 50: 79–88.
[28] MURMANN J P, FRENKEN K. Toward a systematic framework for research on dominant designs, technological innovations, and industrial change. Research Policy, 2006, 35: 925–952.
[29] UTTERBACK J M, ABERNATHY W J. A dynamic model of process and product innovation. Omega, 1975, 3(6): 639–656.
[30] BERKELEY N, BAILEY D, JONES A, et al. Assessing the transition towards battery electric vehicles: a multilevel perspective on drivers of, and barriers to, take up. Transportation Research Part A Policy & Practice, 2017, 106: 320–332.
[31] HOLLAND J H. Complex adaptive system. Reading: Addison Wesley, 1995.
[32] HAURAND M D, STUMMER C. Stakes or garlic? Studying the emergence of dominant designs through an agent-based model of a vampire economy. Central European Journal of Operations Research, 2018, 26(2): 373–394.
[33] RAND W M, RUST R T. Agent-based modeling in marketing: guidelines for rigor. International Journal of Research in Marketing, 2011, 28(3): 181–193.
[34] AHRWEILER P, PYKA A, GILBERT N. Simulating knowledge dynamics in innovation networks (SKIN). LEOMBRUNI R, RICHIARDI M, ed. Industry and labor dynamics: the agent-based computational economics approach. Singapore: World Scientific Press, 2004.
[35] MA Q, WU W W, LIU Y X, et al. Impact of the synergy between technology management and technological capability on new product development: a system dynamics approach. Journal of Systems Engineering and Electronics, 2022, 33(1): 105–119.

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