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## EDITED BY

Amin Ul Haq,  
University of Electronic Science and  
Technology of China, China

## REVIEWED BY

Min Yang,  
Chengdu University of Information  
Technology, China  
Xiangjian Weng,  
China Railway Construction  
Corporation Limited, China

## \*CORRESPONDENCE

Haitao Ji,  
✉ [jht02@sut.edu.cn](mailto:jht02@sut.edu.cn)

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# The R&D game of technological achievements in industrial parks under the “administrative committee + enterprise” model: a CPSS perspective

Meng Qiu, Haitao Ji\*, Miao Wang and Jifa Wang

School of Management, Shenyang University of Technology, Shenyang, China

Under the background of digitalization and collaborative innovation, high-tech industrial parks have gradually evolved into complex innovation systems characterized by multi-agent interaction. From the perspective of social physics, this thesis constructs a tripartite evolutionary game model involving high-tech industrial parks under the “administrative committee + enterprise” mode, park technology enterprises, and academic research institutions within the CPSS (Cyber-Physical-Social System) framework, and analyzes the influence mechanisms of key parameters in the information layer, physical layer, and social layer on system stability through replicator dynamic equations and numerical simulation. The results indicate that cooperative R&D of scientific and technological achievements is not a linear process of input accumulation, but a nonlinear evolutionary system driven by cross-layer coupling relationships. The simulation results show that the level of value-added services, as the support intensity of the information layer, exhibits a significant threshold effect. Moderate information support can reduce information asymmetry and promote system convergence toward a collaborative equilibrium, whereas excessively low or excessively high levels may lead to system instability. Investment shareholding changes the stability interval of the system by influencing resource allocation and benefit distribution structures. Appropriate participation contributes to the formation of a risk-sharing mechanism, while excessive shareholding weakens enterprises’ incentives for R&D. The subsidy ratio reflects governance intensity in the social layer. Moderate intervention can promote the formation of collaboration, whereas excessive intervention may cause strategic distortion and system disturbance. Strategic returns constitute a key variable driving the system from a non-cooperative state to a stable collaborative equilibrium. When system-level collaborative benefits exceed a critical threshold, a cross-layer positive feedback mechanism emerges.

## KEYWORDS

administrative committee + enterprise, CPSS, evolutionary game, high-tech industrial parks, scientific and technological achievements research and development

## 1 Introduction

Technological innovation constitutes the core driving force for high-quality economic development, and scientific and technological achievements research and development, as the source stage of the innovation chain, plays a fundamental role in technological

breakthroughs and industrial upgrading. Relying on the agglomeration of innovation resources and the advantages of policy support, high-tech industrial parks have gradually become important carriers for scientific and technological achievements research and development. By the end of 2024, high-tech industrial parks in China had gathered a large number of high-tech enterprises and innovation entities, continuously promoting the development of new technologies and emerging industries through the concentrated allocation of innovation factors. However, with the increasing complexity of technology and intensified industrial competition, the traditional park governance mode dominated by administrative leadership has gradually revealed limitations in resource allocation efficiency, multi-agent collaboration, and sustained incentives, making it difficult to meet the highly dynamic and uncertain requirements of scientific and technological achievements research and development. To improve governance efficiency and market-oriented operational capacity of industrial parks, China has continuously promoted institutional reforms of development zones at the national level. The “Several Opinions on Promoting the Reform and Innovative Development of Development Zones” (Guobanfa [2017] No. 7) proposed separating government functions from enterprise operations and separating administrative management from state-owned asset management, thereby promoting functional separation between administrative authorities and development and operation entities. Under this background, the “administrative committee + enterprise” mode has gradually taken shape, in which the management committee undertakes public governance and policy coordination functions, while the park operating company is responsible for market-oriented operation and resource integration. This arrangement forms a dual-track structure combining administrative guidance and market mechanisms, providing institutional foundations and organizational support for scientific and technological achievements research and development. With the deep application of digital technologies in park governance and research and development activities, the process of scientific and technological achievements research and development has increasingly exhibited the characteristics of Cyber-Physical-Social Systems (CPSS). Structurally, digital platforms and data systems constitute the information layer, enabling information sharing and process coordination in research and development activities; experimental platforms, pilot-testing bases, and industrialization carriers constitute the physical layer, providing fundamental support for technology validation and engineering transformation; policy incentives, institutional arrangements, and multi-agent collaboration mechanisms constitute the social layer, guiding behavioral choices and benefit distribution among participating entities. The information layer, physical layer, and social layer form dynamic interactions through data feedback, resource flows, and institutional regulation. Digital platforms in industrial parks improve information transparency and collaboration efficiency, research and development infrastructure reduces risks in technology transformation, and policy incentive mechanisms influence the evolutionary direction of agents’ strategies by adjusting benefit structures. In practical operation, differences in objectives and information asymmetry exist among park management entities, park technology enterprises, and academic research institutions, which may lead to insufficient cooperative investment and strategic divergence, thereby affecting

the efficiency of scientific and technological achievements research and development. Under the CPSS context, digitalized management within industrial parks strengthens interconnections among agents, allowing individual strategic adjustments to be amplified through system interactions and to influence overall system stability. The “administrative committee + enterprise” mode reshapes the system’s benefit structure through institutional design and policy regulation, and continuously affects the evolutionary path of the system through information transmission enabled by digital platforms and physical support provided by research and development infrastructure. Under different levels of policy intensity and collaboration, the system evolves from a non-cooperative state toward a stable cooperative equilibrium [1].

Based on this, this thesis constructs a multi-agent evolutionary game model within the CPSS analytical framework to systematically analyze the interaction mechanisms and evolutionary paths of cooperative scientific and technological achievements research and development in high-tech industrial parks under the “administrative committee + enterprise” mode. The study focuses on revealing the formation mechanism of system stability under the coordinated effects of digitalized management, research and development infrastructure, and policy incentives, thereby providing theoretical support and practical implications for collaborative governance of industrial parks and scientific and technological achievements research and development from the perspective of social physics.

## 2 Literature review

### 2.1 Functions and governance models of high-tech industrial parks

High-tech industrial parks, as important institutional carriers for implementing the innovation-driven development strategy, rely on advantages such as policy support, resource concentration, and institutional innovation, and play a key hub role in China’s regional innovation system [2, 3]. Existing studies generally argue that high-tech industrial parks effectively enhance regional innovation efficiency and the quality of economic growth by improving the innovation environment, reducing institutional transaction costs, and promoting the agglomeration of innovation factors [4, 5]. With the deepening integration of science and technology into industry, high-tech industrial parks have gradually evolved from spaces of single-factor agglomeration into comprehensive innovation platforms that connect academic research institutions, enterprises, and government. Their platform attributes and governance structures have become important factors influencing innovation performance [6, 7]. In addition, the policy regulations and institutional arrangements of high-tech industrial parks constitute key conditions for promoting the coordinated coupling and development of innovation actors such as industry, universities, research, and finance [8]. Within such institutional support, enterprises, universities, and research institutes in the parks are able to realize knowledge production, transfer, and integration [9, 10], thereby significantly strengthening the level of cooperation among innovation actors [11].

In terms of governance models, the “administrative committee + enterprise” model is regarded as a typical governance form that combines administrative functions with market mechanisms. By separating public management functions from market-oriented operational functions, this model aims to improve the efficiency of resource allocation and the level of public services in industrial parks [12, 13]. This governance model, which integrates market entities and administrative entities, has effectively enhanced the development level of high-tech industrial parks [14]. However, it also inherently involves risks of power overlap and governance challenges [15], and its governance scale is closely related to economic performance [16]. Notably, some studies have begun to focus on the guiding role of industrial parks in cooperative innovation. For example, [17], from the perspective of evolutionary game theory, revealed that administrative committees can promote the formation of cooperative innovation networks between core enterprises and small and medium-sized enterprises through policy support and regulatory mechanisms [18], by constructing a tripartite game among science cities, enterprises, and academic research institutions, proposed that the supervision and punishment mechanisms of science cities have a significant impact on the strategy choices of collaborative innovation actors such as enterprises and academic research institutions [18]. These studies provide a preliminary game-theoretic basis for understanding the role of park management entities in innovation cooperation, but they have not yet deeply characterized the game behaviors of industrial parks as composite actors with both policy and market attributes under the “administrative committee + enterprise” model in industry—university—research cooperation.

## 2.2 Collaborative multi-actor mechanisms in industry—University—Research cooperation

Scientific and technological achievements research and development relies heavily on collaboration among multiple actors, among which industry—university—research cooperation constitutes a key organizational form [19]. Existing studies mainly adopt two perspectives. The first emphasizes the institutional coordination role of government, arguing that through subsidies, regulation, and public services, government intervention can mitigate information asymmetry and guide the stability of cooperation [20, 21]. For example, some studies have constructed government-led bi-level planning models to coordinate public interests and enterprise operational optimization [22] or demonstrated that appropriate subsidies can promote the positive evolution of integrated innovation systems among large, medium, and small enterprises [23]. The second perspective highlights the leading role of enterprises in multi-actor collaborative innovation [24, 25]. When facing changes in the external environment, enterprises actively adjust their innovation strategies and strengthen industry—university—research cooperative innovation, thereby significantly improving the level of such cooperation [26]. Moreover, enterprises’ absorptive capacity is identified as a key factor influencing the evolutionary outcomes of collaborative innovation in major scientific research infrastructure within industry—university—research systems [27].

## 2.3 Application of evolutionary game theory in modeling multi-actor innovation systems

With the increasing complexity and uncertainty of innovation systems, evolutionary game theory has become an important theoretical tool for analyzing multi-actor innovation decision-making, as it is able to describe strategy adjustment and equilibrium formation of boundedly rational actors in dynamic interactions [28, 29]. Evolutionary game theory originates from ideas of biological evolution, and its core concepts, such as replicator dynamics and evolutionary stable strategies (ESS), provide a formal analytical framework for studying the evolution of group behavior [30]. [31] systematically elaborated the application of evolutionary games on social networks, laying a methodological foundation for research on networked innovation cooperation [31]. In the field of technological innovation research, this theory has been widely applied to analyze the behavioral evolution of enterprises, governments, academic research institutions, and intermediary organizations in cooperative R&D, technology diffusion, and standard competition [1]. In recent years, scholars have constructed various multi-actor evolutionary game models to reveal the stability mechanisms of innovation cooperation. For example, [32] examined the long-term mechanisms of responsible innovation from a multi-actor behavioral evolution perspective [32]. [33] analyzed the impact of government subsidies on technological games among actors in innovation ecosystems [33], and [34] investigated the evolution of regional military—civilian collaborative technological innovation ecosystems based on multi-actor games [35]. These studies generally indicate that institutional incentives, capability differences, and network structures can drive systems toward different equilibrium states by altering the payoff structure.

In summary, the existing literature mainly develops from three aspects: first, studies on the functional positioning and governance modes of high-tech industrial parks; second, analyses of collaborative cooperation mechanisms among industry, universities, and research institutions in technological innovation; and third, studies on the application of evolutionary game methods in innovation decision-making. Although these studies provide important theoretical foundations and empirical support for understanding the process of scientific and technological achievements research and development, certain limitations remain under the CPSS context. First, existing multi-agent game studies mainly focus on the traditional structure of “government—enterprise—academic research institutions,” and seldom examine high-tech industrial parks from a CPSS perspective as integrated systems that combine physical spatial carriers, digital governance platforms, and social coordination mechanisms, or analyze them as independent decision-making agents with autonomous strategic choices. Second, research on collaborative innovation among high-tech industrial parks, industry, universities, and research institutions largely remains at the level of descriptive analysis or policy evaluation, lacking systematic modeling analysis of strategic evolution among agents, governance constraints, and mechanisms of collaborative stability in digital interactive environments, and thus has not fully revealed the influence mechanism of multi-agent interaction within the CPSS structure

on scientific and technological achievements research and development behavior.

Based on this, this thesis takes the practical operational mode of “administrative committee + enterprise” in high-tech industrial parks as the research background. Within the framework of evolutionary game analysis, high-tech industrial parks are defined as decision-making agents possessing both institutional regulation and resource allocation functions. A tripartite evolutionary game model involving high-tech industrial parks, park technology enterprises, and academic research institutions is constructed to systematically analyze the effects of changes in key parameters on system stability structures and the transition path toward collaborative equilibrium. From the CPSS perspective, this study reveals the institutional regulation and collaborative governance roles played by high-tech industrial parks in the process of scientific and technological achievements research and development, thereby providing a new theoretical explanation for understanding innovation governance mechanisms of industrial parks under the digitalization context.

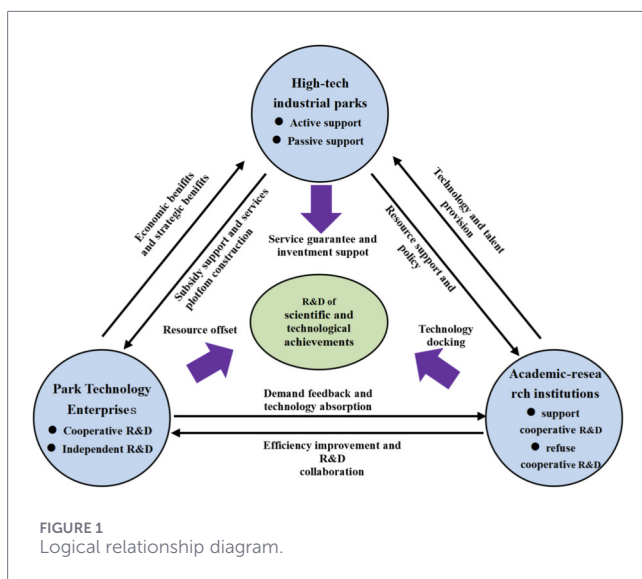
### 3 Scenario description and basic assumptions

Within the innovation ecosystem of high-tech industrial parks, scientific and technological achievements research and development, as the starting point of the scientific and technological achievements transformation chain, usually involves three core actors: the park management authority (hereinafter referred to as the park), park technology enterprises, and academic research institutions. Its operation process is reflected not only as the organization of technological research and development activities, but also as a dynamic interaction among multiple agents in resource allocation, risk sharing, and benefit distribution. High-tech industrial parks undertake important functions of resource integration and collaborative organization in this process. Under the “administrative committee + enterprise” model, a structural separation is realized between the park’s administrative management functions and market-oriented operation mechanisms. The administrative committee shapes the innovation environment through policy formulation and institutional supply, while the platform company provides capital operation and professional services based on market mechanisms. Together, they form a “dual field” that guides innovation behavior within the park [35], thereby providing institutional support and market incentives for industry—university—research cooperation. From the CPSS perspective, scientific and technological achievements research and development can be understood as a complex collaborative process characterized by the deep coupling of information flows, physical resources, and social relations. At the information layer, the park integrates policy information, technological demands, and research output data through digital management platforms and service systems, thereby reducing information asymmetry. Park technology enterprises make R&D decisions based on market demand and technical data, and improve technology matching efficiency through information sharing. Academic research institutions output research information and innovative solutions based on knowledge production and technological accumulation. Through continuous information interaction, the three parties adjust their

cooperative expectations and behavioral strategies. At the physical layer, the park provides technical validation and engineering support by constructing R&D carriers, pilot-testing platforms, and shared facilities. Park technology enterprises undertake tasks of technology development and product implementation, while academic research institutions provide experimental conditions and technical prototypes. Together, they form the physical support system that enables scientific and technological achievements to move from laboratories to industrialization. At the social layer, the park shapes cooperative trust and governance structures through institutional arrangements and incentive mechanisms. Park technology enterprises and academic research institutions gradually form stable collaborative network relationships through long-term cooperation. Reputation mechanisms, risk sharing, and interest coordination become important factors driving the continuous evolution of cooperation. Efficient information flow in the information layer provides decision-making support for resource allocation in the physical layer. R&D practices in the physical layer continuously generate new technical data and feed it back into the information system. Meanwhile, trust structures and institutional arrangements in the social layer ensure the sustained operation of information sharing and resource coordination. The three layers form an organically linked mechanism characterized by mutual embedding and dynamic feedback in the process of scientific and technological achievements research and development, making R&D activities exhibit typical CPSS collaborative features.

Under this institutional and systemic environment, the strategic choices of high-tech industrial parks, park technology enterprises, and academic research institutions are reflected as dynamic trade-offs among costs, benefits, and capabilities under multidimensional coupling conditions. After evaluating expected innovation benefits, resource integration capacity, and system operation risks, the park chooses between active support and maintaining basic services. Its support behavior not only influences the intensity of physical resource investment but also changes the transmission efficiency of cooperative signals through information platforms and institutional arrangements. Park technology enterprises make trade-offs between independent R&D and cooperative R&D, considering both technological exclusivity and R&D risks, while also evaluating efficiency improvements brought by information sharing and the risks of technology spillover. Academic research institutions choose between supporting cooperation and maintaining research autonomy, and their decisions are influenced by factors such as access to research resources, efficiency of scientific and technological achievements transformation, and academic reputation. Therefore, from the CPSS perspective, the multi-agent strategic evolution of scientific and technological achievements research and development in high-tech industrial parks is no longer driven solely by economic returns, but represents a systemic equilibrium process formed through the joint effects of information interaction, physical investment, and social governance. The behavioral logic among the three game participants is illustrated in the following [Figure 1](#):

To facilitate analysis and strengthen the theoretical and empirical foundation of the model, this study, based on the integration of innovation ecosystem theory, evolutionary game methods, and relevant empirical research, makes the following assumptions.



**Assumption 1:** Based on evolutionary game theory [28] and bounded rationality decision theory [36], high-tech industrial parks (hereafter referred to as the parks), park technology enterprises, and academic research institutions are regarded as bounded rational agents engaging in long-term interactions within a complex innovation ecosystem. Their strategy choices are not one-time optimal decisions but gradually form through an evolutionary process of trial-error-feedback-adjustment [37]. Specifically, the probability that a high-tech industrial park adopts an active support strategy is  $x$  ( $0 < x < 1$ ), and the probability of choosing a passive support strategy is  $1-x$ . Park technology enterprises, as initiators of R&D, choose cooperative R&D with academic research institutions with probability  $y$  ( $0 < y < 1$ ), and independent R&D with probability  $1-y$ . Academic research institutions choose to support cooperative R&D with probability  $z$  ( $0 < z < 1$ ), and to refuse cooperative R&D with probability  $1-z$ . The strategy probabilities of each agent dynamically adjust during the evolutionary process in accordance with the fundamental setting of evolutionary games that “strategy proportions evolve with relative payoff,” aligning with the real-world features of multi-agent long-term interaction and path dependence in innovation activities.

**Assumption 2:** Based on innovation ecosystem theory [38] and platform governance theory [39], under the “administrative committee + enterprise” mode, the park no longer functions only as a provider of basic spatial support, but jointly participates in the process of scientific and technological achievements research and development through institutional supply and market-oriented operation. As a result, their revenue structure shifts from reliance on basic service income toward a composite structure in which collaborative innovation returns and capital returns coexist. From the CPSS perspective, this revenue structure originates from the park’s systemic regulatory capacity across the information layer, physical layer, and social layer. Specifically, under normal operating conditions, the park obtains basic service income while bearing basic operating costs  $C_1$ . When the park chooses active support for cooperative R&D, it intervenes in the process of

scientific and technological achievements research and development through the construction of information platforms, investment in R&D infrastructure, and the provision of policy incentives, thereby obtaining strategic returns  $R_c^o$  and economic returns. Strategic returns are mainly reflected in strengthened industrial agglomeration, enhanced technology spillover, and improvement of the innovation ecosystem, representing long-term systemic benefits formed through cross-layer collaboration. Specifically, the economic returns of the park can be divided into the following three levels:

### 3.1 Physical layer: participation in pilot-testing platforms and R&D infrastructure investment to obtain returns

At the physical layer, the park provides key support for the transition of scientific and technological achievements from experimental validation to engineering application through the construction of pilot-testing platforms, experimental facilities, and shared R&D infrastructure. According to industrial investment theory [40] and risk-sharing theory [41], the park may participate in R&D project investment through capital increase, equity participation, or convertible bonds. It is assumed that the project investment cost is  $C_c^p = \alpha E$ , and the corresponding return is  $R_c^p = \alpha R_m$  according to the shareholding ratio, where  $\alpha$  represents the proportion of shares held by the park in the R&D project, reflecting the depth of the park’s participation in resource allocation and risk bearing in the R&D process, and  $E$  denotes the total cost of the R&D project. This setting reflects that investment in physical-layer infrastructure generates returns by reducing technology maturation risks and improving the feasibility of scientific and technological achievements. Following the basic principle of “bearing costs and sharing returns according to the investment proportion,” the park receives dividend returns based on its shareholding ratio after the successful completion of the R&D project.

### 3.2 Returns from digital platforms, information services, and data governance

In this study, value-added services provided by the park are understood as a comprehensive collaborative support capability with digital platforms as the core carrier. The mechanism operates in two main ways. On the one hand, information integration and data sharing reduce information asymmetry between park technology enterprises and academic research institutions, thereby lowering communication and coordination costs during cooperative R&D. On the other hand, data feedback and performance evaluation provide decision-making support for the park in formulating subsidy policies, adjusting support intensity, and optimizing resource allocation, thus enhancing the stability and sustainability of multi-agent cooperative R&D. Referring to the quadratic cost function widely adopted in the literature on platform economics and service provision, the construction cost of value-added services is assumed to be  $\frac{1}{2}K(1 + \delta)^2$  [42], where  $K$  represents the unit cost coefficient of value-added service level and  $\delta$  ( $0 < \delta < 1$ ) denotes the level of value-added services. This cost structure reflects the characteristic of increasing marginal cost, indicating that as service depth and complexity increase, the platform’s investment

in professional talent introduction, system maintenance, and organizational coordination rises significantly, which is consistent with the theoretical expectations of diminishing returns to scale and service complexity. Correspondingly, the return obtained by the park from value-added services is set as  $T\delta$ , where  $T$  represents the unit return of value-added service level. This return not only derives from direct service income but also reflects improvements in collaborative efficiency, aggregation of innovation resources, and long-term strategic value growth of the park resulting from optimized information flows.

### 3.3 Social layer: returns mechanism of policy incentives and institutional arrangements

At the social layer, the park regulates interactions among multiple agents through institutional arrangements and policy incentives. The park provides incentives for cooperative R&D through subsidies, with the subsidy amount expressed as  $S_1 = R_j^p \phi$ , where  $R_j^p$  represents the R&D funding paid by park technology enterprises to academic research institutions, and the parameter  $\phi$  ( $0 < \phi < 1$ ) denotes the park's subsidy ratio, reflecting the strength of governance regulation at the social layer. This setting is based on widely adopted matching subsidy mechanisms in practice. From the CPSS perspective, it reflects the intensity of social-layer governance regulation, serving to lower the barriers to cooperation and strengthen cooperative expectations.

**Assumption 3:** Based on the theory of collaborative innovation [43] and innovation ecosystem theory [38], the R&D decisions of park technology enterprises are jointly influenced by the information environment, physical support conditions, and institutional environment. Their strategy choice depends on whether the total benefits generated from cooperative R&D can cover the R&D risks and collaboration costs. Within the CPSS framework, enterprise returns arise from the combined effects of all three layers. The returns of park technology enterprises under cooperative R&D include:

### 3.4 Strategic returns $R_i^o$ (result of social-layer effects)

Strategic returns primarily reflect the enhancement of technological collaboration capabilities, integration of industrial chain resources, and the improvement of the park's position within the regional innovation network through collaboration among park technology enterprises, academic research institutions, and the park. These returns arise from the long-term value generated by institutional trust and the stability of multi-agent relationships.

### 3.5 Cooperative R&D subsidy $S_1$ (social-layer incentive mechanism)

This refers to the policy support provided by the high-tech industrial park to promote cooperative R&D, aimed at reducing uncertainty and risk costs for enterprises during the initial stages of collaboration.

## 3.6 Project economic returns $R_i^p$ (result of combined effects from information, physical, and social layers)

The expected economic return of a project's R&D success is given by  $R_i^p = \beta R_m w p$ , where  $R_m$  represents the total economic return after the R&D project succeeds,  $\beta$  denotes the share proportion of the park technology enterprises in the R&D project, with  $\alpha + \beta = 1$  ( $0 \leq \alpha, \beta \leq 1$ ),  $w$  is the R&D efficiency, and  $p$  is the probability of R&D success. This allocation of returns aligns with the mechanism of shared risk and shared benefits [44].

Based on service empowerment theory [45] and research on innovation support environments [46], this study assumes that R&D efficiency  $w$  results from the combined effects of the information layer, physical layer, and social layer. When the park adopts an active support strategy, the value-added services of the park's digital platform (information layer), policy incentives (social layer), and the provision of public R&D platforms and experimental facilities (physical layer) can reduce information asymmetry and R&D trial-and-error costs, thereby enhancing R&D efficiency. Specifically, the basic R&D efficiency  $w_2$  is increased to  $w_1 = w_2 + (1-w_2)\delta$  [47]. According to findings from innovation environment studies regarding "differentiation in R&D performance caused by support intensity" [48], this setting indicates that digital platforms do not directly alter the enterprises' inherent R&D capabilities but instead improve marginal efficiency by enhancing information flows and resource allocation. Drawing on knowledge complementarity theory [49] and inter-organizational learning theory [50], the R&D success rate under cooperative R&D is denoted as  $p_1$ , and the success rate under independent R&D is denoted as  $p_2$ , with the assumption that  $p_2 < p_1$  ( $0 < p_1, p_2 < 1$ ). This assumption reflects the systematic advantages of cooperative R&D in integrating multi-source knowledge, sharing risks, and selecting technological paths.

In terms of costs, based on a structural analysis framework of R&D investment sharing and collaborative innovation costs, park technology enterprises incur the following costs under cooperative R&D.

1. Project R&D cost (physical layer R&D investment cost):  $C_s^p = \beta E$ , where  $E$  represents the total cost of the R&D project. This setting reflects that enterprises share R&D investment proportionally to their equity stake.
2. Cooperative R&D strategic cost (social layer coordination cost):  $C_i^o$ , which captures the implicit costs arising from increased organizational coordination, knowledge sharing, and management complexity during the collaboration process.
3. Park value-added service cost  $T\delta$  and basic service cost  $U$  (information layer and basic service expenses), representing the fees paid by enterprises to access different levels of park services.
4. R&D funding paid to academic research institutions  $R_j^o$ , reflecting the practical allocation of enterprise investment in research resources within the industry–university–research collaboration.

This cost structure indicates that park technology enterprises are subject to the dual influence of physical layer investment constraints and social layer coordination constraints.

**Assumption 4:** Based on collaborative innovation theory [43] and reputation theory [51, 52], when academic research institutions choose to engage in cooperative R&D with park technology enterprises, their motivation is derived not only from direct economic returns but also from the long-term enhancement of academic and social value generated through such collaboration. Specifically, the benefits obtained by academic research institutions under cooperative R&D mainly consist of two components:

1. Strategic returns  $R_j^o$  (Result of the social layer): These include, but are not limited to, improvements in academic reputation, expansion of the influence of scientific and technological achievements transformation, extension of application scenarios for research outcomes, and enhanced capacity to secure future research projects and funding. Existing studies indicate that a key motivation for academic research institutions to participate in industry-university-research collaboration lies in strengthening academic impact and social service functions through achievement transformation [53].
2. Economic returns  $R_j^p$  (Return on R&D investment in the physical layer): These refer to the R&D funds paid by park technology enterprises to academic research institutions for cooperative R&D, which are used to support research activities, researcher engagement, and the provision of experimental conditions.

At the same time, academic research institutions must also bear corresponding costs when choosing cooperative R&D, which mainly include.

1. Economic costs  $C_j^p$ : Such as expenses for experimental equipment usage, labor costs of research personnel, and other direct expenditures incurred during the R&D process.
2. Strategic costs  $C_j^o$ : These describe the opportunity costs arising from cooperative R&D for the internal allocation of research resources within academic research institutions, including the occupation of academic resources, dispersion of research team efforts, crowding out of time devoted to basic research, and potential constraints on academic research directions.

Based on the basic principles of rational decision-making theory and cost-benefit analysis, this thesis assumes that academic research institutions have intrinsic motivation to participate in cooperative R&D if and only if  $R_j^o + R_j^p > C_j^o + C_j^p$  [54]. This inequality characterizes the rational constraint for academic research institutions' participation in cooperative R&D, indicating that such cooperation is feasible and sustainable only when the total benefits of collaboration exceed the economic and strategic costs borne by the institutions. The specific parameters are shown in Table 1.

## 4 Model construction and stability analysis

Based on the relationships among the participants in scientific and technological achievements R&D projects under the “administrative committee + company” model and the underlying assumptions, the payoff matrix for the

three game participants—high-tech industrial parks, park technology enterprises, and academic research institutions—is presented in Table 2.

### 4.1 Model construction of the game

In this study, the strategy selection probabilities of the three parties are regarded as order parameters that characterize the macroscopic state of the system, and replicator dynamic equations are employed to describe the temporal evolution of different strategies within the population. The specific process is described as follows:

The expected payoffs of the high-tech industrial parks under active support and passive support are denoted as  $E_{c1}$  and  $E_{c2}$ , respectively. The average payoffs is  $E_{c3}$ , the expected payoffs and average payoffs are shown in Equation 1.

$$\begin{aligned}
 E_{c1} &= yz \left( U + \alpha R_m w_1 p_1 + T\delta + R_c^o - \frac{1}{2} K(1 + \delta)^2 - \alpha E - C_1 - R_j^p \right) \\
 &\quad + y(1-z) \left( U + \alpha R_m w_1 p_2 + T\delta + R_c^o - \frac{1}{2} K(1 + \delta)^2 - \alpha E - C_1 \right) \\
 &\quad + (1-y)z \left( U + \alpha R_m w_1 p_2 + T\delta + R_c^o - \frac{1}{2} K(1 + \delta)^2 - \alpha E - C_1 \right) \\
 &\quad + (1-y)(1-z) \left( U + \alpha R_m w_1 p_2 + T\delta + R_c^o - \frac{1}{2} K(1 + \delta)^2 - \alpha E - C_1 \right) \\
 E_{c2} &= yz(U - C_1) + y(1-z)(U - C_1) + (1-y)z(U - C_1) + (1-y)(1-z)(U - C_1) \\
 E_{c3} &= xE_{c1} + (1-x)E_{c2}
 \end{aligned} \tag{1}$$

Based on the framework of the malthusian replicator dynamics. The replicator dynamic equation of Park as shown in Equation 2.

$$P(x) = \frac{dx}{dt} = (E_{c1} - E_{c3})x = x(1-x) \left[ \begin{aligned} &aR_m w_1 (p_2 + yz(p_1 + p_2)) + T\delta \\ &+ R_c^o - \frac{1}{2} K(1 + \delta)^2 - \alpha E - yzR_j^p \theta \end{aligned} \right] \tag{2}$$

Similarly, the expected payoffs of park technology enterprises choosing cooperative R&D and independent R&D strategies are denoted as  $E_{p1}$  and  $E_{p2}$ , respectively. The average payoffs is  $E_{p3}$ , the expected payoffs and average payoffs are shown in Equation 3.

$$\begin{aligned}
 E_{p1} &= xz(\beta R_m w_1 p_1 + R_i^o - R_j^o(1-\phi) - \beta E - C_i^o - T\delta - U) + (1-x)z(R_m w_2 p_1 + R_i^o - R_j^o - E - C_i^o - U) \\
 &\quad + x(1-z)(\beta R_m w_1 p_2 - \beta E - C_i^o - T\delta - U) + (1-x)(1-z)(R_m w_2 p_2 - E - C_i^o - U) \\
 E_{p2} &= xz(\beta R_m w_1 p_2 - \beta E - T\delta - U) + (1-x)z(R_m w_2 p_2 - E - U) \\
 &\quad + x(1-z)(\beta R_m w_1 p_2 - \beta E - T\delta - U) + (1-x)(1-z)(R_m w_2 p_2 - E - U) \\
 E_{p3} &= yE_{p1} + (1-y)E_{p2}
 \end{aligned} \tag{3}$$

The replicator dynamic equation of park technology enterprises is expressed as Equation 4:

$$M(y) = dy/dt = (E_{p1} - E_{p3})y = y(1-y) \left[ \begin{aligned} &-C_i^o + z(R_i^o - R_j^o + R_j^o \phi x) \\ &+ z(p_1 - p_2)(\beta R_m w_1 x + R_m w_2(1-x)) \end{aligned} \right] \tag{4}$$

Similarly, the expected payoffs of the academic research institutions for choosing to support cooperative R&D and to reject

TABLE 1 Model parameters and explanations.

Parameters	Meaning	Parameters	Meaning
$U$	The basic service revenues of the high-tech industrial parks	$R_i^o$	Strategic benefits of park technology enterprises
$C_1$	The basic cost paid by the high-tech industrial parks	$R_i^p$	Economic return of park technology enterprises
$R_c^o$	The strategic benefits obtained by the high-tech industrial parks	$R_j^p$	The economic benefits of academic research institutions
$R_c^p$	The strategic benefits of high-tech industrial parks	$R_j^o$	The strategic benefits of academic research institutions
$C_c^p$	The project investment cost	$\beta$	Shareholding ratio of park technology enterprises
$E$	Total cost of the R&D project	$w$	R&D efficiency
$\alpha$	Share holding proportion of the high-tech industrial parks in the R&D project	$p_1, p_2$	The success rate of cooperative R & D and independent R&D
$K$	Cost coefficient of the unit level of value-added service	$\delta$	The level of value-added service
$R_c^p$	Park obtains returns through dividends distributed in proportion to its shareholding	$C_s^p$	The R&D costs of park technology enterprises include the project R&D cost
$R_m$	Total revenue of the successful R&D project	$C_i^o$	The strategic cost of collaboration of park technology enterprises
$\phi$	Subsidy ratio provided	$C_j^o$	The strategic cost of academic research institutions
$S_1$	Cooperative R & D subsidies given to enterprises by high-tech industrial parks	$C_j^p$	The economic cost of academic research institutions
$T$	Revenue per unit level of value-added service	$w_1 w_2$	The R & D efficiency under the positive and negative support of the park

TABLE 2 Three-player game payoff matrix among high-tech industrial parks, park technology enterprises, and academic research institutions.

Strategy		Active support of high-tech industrial parks x	Passive support 1-x
Park technology enterprise cooperative R&D $y$	Academic research institutions choose to support cooperative R&D $z$	$U + \alpha R_m w_1 p_1 + T\delta + R_c^o - \frac{1}{2}K(1 + \delta)^2 - \alpha E - C_1 - R_j^p \phi$	$U - C_1$
		$\beta R_m w_1 p_1 + R_i^o - R_j^p(1 - \phi) - \beta E - C_i^o - T\delta - U$	$R_m w_2 p_1 + R_i^o - R_j^p - E - C_i^o - U$
		$R_j^p + R_j^o - C_j^p - C_j^o$	$R_j^p + R_j^o - C_j^p - C_j^o$
	Academic research institutions choose to refuse cooperative R&D $1-z$	$U + \alpha R_m w_1 p_2 + T\delta + R_c^o - \frac{1}{2}K(1 + \delta)^2 - \alpha E - C_1$	$U - C_1$
		$\beta R_m w_1 p_2 - \beta E - C_i^o - T\delta - U$	$R_m w_2 p_2 - E - C_i^o - U$
		0	0
Park technology enterprise independent R&D $1-y$	Academic research institutions choose to support cooperative R&D $z$	$U + \alpha R_m w_1 p_2 + T\delta + R_c^o - \frac{1}{2}K(1 + \delta)^2 - \alpha E - C_1$	$U - C_1$
		$\beta R_m w_1 p_2 - \beta E - T\delta - U$	$R_m w_2 p_2 - E - U$
		$-C_j^o$	$-C_j^o$
	Academic research institutions choose to refuse cooperative R&D $1-z$	$U + \alpha R_m w_1 p_2 + T\delta + R_c^o - \frac{1}{2}K(1 + \delta)^2 - \alpha E - C_1$	$U - C_1$
		$\beta R_m w_1 p_2 - \beta E - T\delta - U$	$R_m w_2 p_2 - E - U$
		0	0

cooperative R&D are denoted as  $E_{s1}$  and  $E_{s2}$ , respectively. The average payoffs is  $E_{s3}$ , the expected payoffs and average payoffs are shown in Equation 5.

$$\begin{aligned}
 E_{s1} &= xy(R_j^p + R_j^o - C_j^p - C_j^o) + (1-x)y(R_j^p + R_j^o - C_j^p - C_j^o) \\
 &\quad + x(1-y)(-C_j^o) + (1-x)(1-y)(-C_j^o) \\
 E_{s2} &= 0 \\
 E_{s3} &= zE_{s1} + (1-z)E_{s2}
 \end{aligned}
 \tag{5}$$

The replicator dynamic equation of the academic research institutions is expressed as Equation 6.

$$U(z) = dz/dt = (E_{s1} - E_{s3})z = z(1-z)[y(R_j^p + R_j^o - C_j^p) - C_j^o] \tag{6}$$

## 4.2 Evolutionary stability analysis

### 4.2.1 Evolutionary path and stability analysis of the high-tech industrial parks

Based on the replicator dynamic equation model, this thesis conducts an in-depth exploration of the dynamic evolutionary paths and stable states of the three game participants when the parks choose the strategy of active support, the park technology enterprises choose cooperative R&D, and the academic research institutions choose to support cooperation. The stability conditions are as follows:  $p(x) = 0, \partial p(x)/\partial x < 0; M(y) = 0, \partial M(y)/\partial y < 0; U(z) = 0, \partial U(z)/\partial z < 0$ .

Let  $p(x) = 0$ , the solutions are  $x = 1, x = 0, z = z^*$ . When  $z^* = -\frac{\alpha R_m w_1 p_2 + T\delta + R_c^o - \alpha E - \frac{1}{2}K(1+\delta)^2(y(1+K\delta) - K\delta)}{y(\alpha R_m w_1(p_1 - p_2) - R_j^p \phi) - \frac{1}{2}K(1+\delta)^2(1+K\delta)(1-y)}$  then  $p(x) \equiv 0$  and any value of  $x$  represents a stable strategy, the corresponding stable states in the system's evolutionary process. When  $z^* < -\frac{\alpha R_m w_1 p_2 + T\delta + R_c^o - \alpha E - \frac{1}{2}K(1+\delta)^2(y(1+K\delta) - K\delta)}{y(\alpha R_m w_1(p_1 - p_2) - R_j^p \phi) - \frac{1}{2}K(1+\delta)^2(1+K\delta)(1-y)}$  and  $y(\alpha R_m w_1(p_1 - p_2) - R_j^p \phi) - \frac{1}{2}K(1+\delta)^2(1+K\delta)(1-y) > 0, x = 1$ , satisfies  $p(x) = 0, \partial p(x)/\partial x < 0$ . This indicates that the parks choose the active support strategy. From the perspective of the payoff-driven mechanism in evolutionary games, this stability condition essentially requires that the expected return of the parks under the "active support" strategy exceeds that under the "passive support" strategy. In other words, the relevant payoff difference is positive, and when this difference crosses the zero threshold, the park's strategy shifts from an unstable state to an asymptotically stable state. When  $z^* < -\frac{\alpha R_m w_1 p_2 + T\delta + R_c^o - \alpha E - \frac{1}{2}K(1+\delta)^2(y(1+K\delta) - K\delta)}{y(\alpha R_m w_1(p_1 - p_2) - R_j^p \phi) - \frac{1}{2}K(1+\delta)^2(1+K\delta)(1-y)}$  and  $y(\alpha R_m w_1(p_1 - p_2) - R_j^p \phi) - \frac{1}{2}K(1+\delta)^2(1+K\delta)(1-y) > 0, x = 0$  satisfies  $(x) = 0, \partial p(x)/\partial x < 0$ , making  $x = 0$  a stable strategy point, the corresponding stable states in the system's evolutionary process. This means that the parks choose the passive support strategy. From the above expressions, it can be observed that the strategic choice of the high-tech industrial parks is not only influenced by the strategies of the park technology enterprises and the academic research institutions, but also affected by multiple factors such as the strategic revenue of the parks  $R_c^o$  the equity proportion in the R&D project  $\alpha$ , the level of value-added services  $\delta$ , and the subsidy ratio  $\phi$  of the parks.

### 4.2.2 Evolutionary path and stability analysis of park technology enterprises

Similarly, when  $x^* = \frac{-C_i^o + z((R_i^o - R_j^o) + R_m(p_1 - p_2)w_2)}{z(R_j^p \phi + R_m(p_1 - p_2)(\beta w_1 - w_2))}$ ,  $M(y) \equiv 0$ , and any value of  $y$  represents a stable strategy, the corresponding stable states in the system's evolutionary process. When  $x^* < \frac{-C_i^o + z((R_i^o - R_j^o) + R_m(p_1 - p_2)w_2)}{z(R_j^p \phi + R_m(p_1 - p_2)(\beta w_1 - w_2))}$  and  $R_j^p \phi + R_m(p_1 - p_2)(\beta w_1 - w_2) > 0, y = 1$  is the stable strategy point, indicating that park technology enterprises choose cooperative R&D. This corresponds to the stable state in the system's evolutionary process, where park technology enterprises choose cooperative R&D. This result implies that, under this parameter combination, the expected return from selecting "cooperative R&D" exceeds that from "independent R&D." In other words, the payoff advantage of the cooperative strategy constitutes the decisive threshold condition for park technology enterprises to opt for cooperative R&D. When  $x^* > \frac{-C_i^o + z((R_i^o - R_j^o) + R_m(p_1 - p_2)w_2)}{z(R_j^p \phi + R_m(p_1 - p_2)(\beta w_1 - w_2))}$  and  $R_j^p \phi + R_m(p_1 - p_2)(\beta w_1 - w_2) > 0, y = 0$  is the stable strategy point, the corresponding stable states in the system's evolutionary process mean that park technology enterprises choose independent R&D. From the above expressions, it can be observed that the strategic choice of park technology enterprises is closely related to the strategic behavior of the parks. Furthermore, it is also significantly influenced by factors such as the cooperative strategic cost ( $C_i^o$ ), the total revenue from successful R&D projects ( $R_m$ ), the equity proportion in the R&D project ( $\beta$ ), and the park subsidy ratio ( $\phi$ ).

### 4.2.3 Evolutionary path and stability analysis of the academic research institutions

When  $y^* = \frac{C_j^o(1-z+xz)}{R_j^p + R_j^o - C_j^p - C_j^o x}$ ,  $U(z) \equiv 0$ , and any value of  $z$  represents a stable strategy, the corresponding stable states in the system's evolutionary process. When  $y^* < \frac{C_j^o(1-z+xz)}{R_j^p + R_j^o - C_j^p - C_j^o x}$ ,  $z = 1$  is the stable strategy point, the corresponding stable states in the system's evolutionary process, indicating that the academic research institutions choose to support cooperative R&D. This stable state requires that the total benefits obtained by academic research Institutions from participating in cooperative R&D exceed their economic and strategic costs. In other words, the expected payoff difference between cooperation and refusal must be positive, and this inequality constitutes the critical threshold condition for strategy shifts of academic research institutions. When  $y^* > \frac{C_j^o(1-z+xz)}{R_j^p + R_j^o - C_j^p - C_j^o x}$ ,  $z = 0$  is the stable strategy point, the corresponding stable states in the system's evolutionary process, indicating that the academic research institutions choose to reject cooperative R&D. From the above equations, it can be observed that the strategy selection of the academic research institutions is directly related to the strategy adopted by the parks, and is also closely associated with the R&D funding  $R_j^p$ , cooperative strategic revenue  $R_j^o$ , and cooperative strategic cost  $C_j^o$ .

### 4.2.4 Evolutionary stability analysis of the three parties

To further explore the formation mechanism of the evolutionary stable strategies under the collaborative interaction among the

TABLE 3 Eigenvalue of equilibrium point and stability analysis.

Point of equilibrium	Eigenvalue $\lambda_1$	Eigenvalue $\lambda_2$	Eigenvalue $\lambda_3$	Stability
$E_1(0,0,0)$	$-\alpha E - \frac{1}{2}K(1+\delta)^2 + R_c^o + \alpha R_m w_1 p_2 + T\delta$	$-C_i^o$	$-C_j^o$	Stabilization
$E_2(1,0,0)$	$\alpha E + \frac{1}{2}K(1+\delta)^2 - R_c^o - \alpha R_m w_1 p_2 - T\delta$	$-C_i^o$	$-C_j^o$	Stabilization
$E_3(0,1,0)$	$-\alpha E - \frac{1}{2}K(1+\delta)^2 + R_c^o + \alpha R_m w_1 p_2 + T\delta$	$C_i^o$	$R_j^p + R_j^o - C_j^o - C_j^p$	Destabilization
$E_4(0,0,1)$	$-\alpha E - \frac{1}{2}K(1+\delta)^2 + R_c^o + \alpha R_m w_1 p_2 + T\delta$	$-C_i^o + R_i^o - R_j^p + R_m w_2 (p_1 - p_2)$	$C_j^o$	Destabilization
$E_5(1,1,0)$	$\alpha E + \frac{1}{2}K(1+\delta)^2 - R_c^o - \alpha R_m w_1 p_2 - T\delta$	$C_i^o$	$R_j^p + R_j^o - C_j^o - C_j^p$	Destabilization
$E_6(1,0,1)$	$\alpha E + \frac{1}{2}K(1+\delta)^2 - R_c^o - \alpha R_m w_1 p_2 - T\delta$	$-C_i^o + R_i^o - R_j^p + R_j^p \phi + R_m \beta w_1 (p_1 - p_2)$	$C_j^o$	Destabilization
$E_7(0,1,1)$	$-\alpha E - \frac{1}{2}K(1+\delta)^2 + R_c^o - R_j^p \phi + \alpha R_m w_1 p_1 + T\delta$	$C_i^o - R_i^o + R_j^p - R_m w_2 (p_1 - p_2)$	$C_j^o - (R_j^p + R_j^o - C_j^p)$	Stabilization
$E_8(1,1,1)$	$\alpha E + \frac{1}{2}K(1+\delta)^2 - R_c^o + R_j^p \phi - \alpha R_m w_1 p_1 - T\delta$	$C_i^o - R_i^o + R_j^p - R_j^p \phi - R_m \beta w_1 (p_1 - p_2)$	$C_j^o - (R_j^p + R_j^o - C_j^p)$	Stabilization

parcs, the park technology enterprises, and the academic research institutions, a more comprehensive analytical method is required. According to the related research of [30], within the analytical framework involving three game participants, the core research focus lies in the analysis of each pure strategy equilibrium point. Based on the previously derived expressions, it can be further clarified that the evolutionary game system jointly composed of the high-tech industrial parks, the enterprises, and the academic research institutions can be represented by the following Jacobian matrix. i.e. the Equation 7.

$$J = \begin{bmatrix} P_x(x) & P_y(x) & P_z(x) \\ M_x(y) & M_y(y) & M_z(y) \\ U_x(z) & U_y(z) & U_z(z) \end{bmatrix} \tag{7}$$

Within the framework of evolutionary games, the evolutionarily stable strategy (ESS) in the model corresponds dynamically to a stable attractor in nonlinear systems. When key parameters shift and cross certain critical thresholds, the original stable equilibrium may destabilize, causing the system's evolutionary trajectory to transition abruptly from the original attractor to a new stable state. This process manifests as a classic phase transition in sociophysical terms, where the system's macroscopic behavior shifts from one stable structure to another. For instance, the transition from a state of "non-cooperative R&D" to one of "stable collaborative R&D" can be interpreted as an evolution from disorder to order. Its underlying driving mechanism stems from the reinforcement of institutional incentives and the optimization of resource allocation structures.

To determine the evolutionary stability and transition process described above (i.e., the stability of the game equilibrium point), this thesis adopts the Lyapunov method [29]. The criterion is as follows: if all eigenvalues of the Jacobian matrix corresponding to an equilibrium point are negative, the equilibrium point is considered an evolutionarily stable strategy; if at least one positive eigenvalue exists in the matrix, the equilibrium point is regarded as unstable. Based on the aforementioned research assumptions, the eight pure strategy equilibrium points within the game system are substituted into the Jacobian matrix for eigenvalue calculation and stability testing. The eigenvalue results and corresponding stability determinations for each equilibrium point are summarized in Table 3.

According to the eigenvalues of the Jacobian matrix corresponding to each equilibrium point in Table 3, the equilibrium points  $E_3(0,1,0)$ ,  $E_4(0,0,1)$ ,  $E_5(1,1,0)$ ,  $E_6(1,0,1)$  contain positive eigenvalues and are therefore unstable points. The stability of the remaining four equilibrium points can be further discussed based on specific conditions. When the strategic cost of cooperation between the park technology enterprises and the academic research institutions is relatively high, both parties, guided by rational cost-benefit considerations, tend to avoid cooperative R&D. At this stage, if the investment subsidies and service costs of the parks in the scientific and technological R&D projects exceed its corresponding revenues, that is,  $\alpha E + \frac{1}{2}K(1+\delta)^2 > R_c^o + \alpha R_m w_1 p_2 + T\delta$ , the parks will adopt a "passive support" strategy, making  $E_1(0,0,0)$  the evolutionarily stable equilibrium of the game system. Conversely, if the park's cost-benefit structure yields a net gain, that is,  $\alpha E + \frac{1}{2}K(1+\delta)^2 < R_c^o + \alpha R_m w_1 p_2 + T\delta$ , the parks will prefer an "active support" strategy, and  $E_2(1,0,0)$  becomes the stable equilibrium. With the continuous iteration of digital technologies, the improvement of the innovation ecosystem, and the optimization of policy support systems, the net revenue obtained by park technology enterprises from cooperative R&D significantly exceeds that from independent R&D. Meanwhile, the academic research institutions' comprehensive income from supporting cooperation can cover both its R&D investment and strategic cooperation costs, that is,  $C_i^o + R_j^p < R_j^p \phi + R_m \beta w_1 (p_1 - p_2) + R_i^o$  and  $C_j^o + C_j^p < R_j^p + R_j^o$ . Under these conditions, both the park technology enterprises and the academic research institutions will shift to the "cooperative R&D" strategy. If, at this time, the investment subsidies and service costs of the high-tech industrial parks still exceed its total benefits, it will continue to maintain a "passive support" strategy, leading the game system to converge to  $E_7(0,1,1)$ . Otherwise, the industrial park will adopt an "active support" strategy, and the game system will eventually stabilize at  $E_8(1,1,1)$ .

The stability of the above three-party joint equilibrium does not depend on the value of a single parameter but is jointly determined by the threshold conditions requiring all participants' payoff differences to be positive simultaneously. When key control parameters—such as the level of value-added services, subsidy ratios, or strategic returns—change and cause the sign of a participant's payoff difference to reverse, the original equilibrium becomes unstable, and the system transitions to a new stable state. It should be noted that, given the three-party evolutionary game

model constructed in this study involves multiple agents, multiple parameters, and nonlinear payoff structures, a complete analytical partitioning of the global parameter space is mathematically complex and is not a conventional approach in multi-agent evolutionary game research. Therefore, this study adopts a research paradigm of “local stability condition analysis combined with numerical simulation validation.” Specifically, the stability of different equilibrium states is characterized by the signs of eigenvalues and payoff difference thresholds, while numerical simulations verify equilibrium transitions under variations of key control parameters. This approach ensures analytical rigor while providing an intuitive representation of how institutional parameters influence the system’s evolutionary trajectories.

## 5 Numerical simulation and analysis

To verify the robustness of the equilibrium results presented in Section 4 and to intuitively reveal the mechanisms by which key parameters affect the system, this section conducts numerical simulations. The model parameters are designed to closely reflect the practical operational logic of the “administrative committee + enterprise” model, drawing on three main sources: (1) reference and adjustment based on commonly used parameter values in existing academic literature; (2) the relative setting of key parameters according to realistic relationships within the cooperative context among the park, enterprises, and academic research institutions; and (3) abstraction of policy tools from the typical park cases introduced in the introduction to map them to model parameters, ensuring the real-world relevance of parameter values. The Xiamen, Chengdu, and Xi’an cases cited in the introduction are not arbitrary examples, rather, they provide real-world prototypes for critical model parameters: the “post-subsidy of R&D funding” policy in Xiamen Torch High-tech Zone corresponds directly to the subsidy ratio  $\phi$ . Chengdu High-tech Zone’s “full lifecycle fund investment system” corresponds to equity investment actions and the equity ratio  $\alpha$  and Xi’an High-tech Zone’s construction of “proof-of-concept and pilot testing shared platforms” corresponds to the level of value-added services  $\delta$  and the resulting R&D efficiency improvement  $w_1$ . This mapping integrates dispersed policy practices into a unified game-theoretic framework, giving the model parameters a solid empirical foundation and supporting the exploration of common evolutionary patterns in multi-actor cooperation in scientific and technological achievements research and development under the “administrative committee + enterprise” model.  $\alpha E + \frac{1}{2}K(1 + \delta)^2 + R_j^p \phi < \alpha R_m w_1 p_1 + R_c^o + T\delta$ ,  $C_i^o + R_j^p < R_m \beta w_1 (p_1 - p_2) + R_j^p \phi + R_c^o$ ,  $C_j^o < (R_j^p + R_j^o - C_j^p)$ . Assuming the initial parameter values are set as follows:  $\alpha = 0.3$ ,  $\beta = 0.7$ ,  $E = 30$ ,  $R_m = 55$ ,  $K = 20$ ,  $\delta = 0.5$ ,  $C_i^o = 3$ ,  $C_j^o = 9$ ,  $R_c^o = 15$ ,  $R_i^o = 8$ ,  $R_j^o = 3$ ,  $R_j^p = 8.6$ ,  $\phi = 0.15$ ,  $T = 15$ ,  $w_1 = 0.75$ ,  $w_2 = 0.5$ ,  $p_2 = 0.7$ ,  $p_1 = 0.9$ . The equity ratios  $\alpha$ ,  $\beta$  are informed by the Chengdu High-Tech Zone’s “full lifecycle fund investment system,” where platform companies typically hold 10%–30% of early-stage projects to balance risk and return. Setting  $\alpha = 0.3$ ,  $\beta = 0.7$  reflects the park’s guiding investment role of “active support without controlling stake.” The Xiamen Torch High-Tech Zone policy stipulates subsidies proportional to enterprises’ R&D expenditures to universities and research institutes. Local subsidy ratios usually range from 10% to 25%,

taking  $\phi = 0.15$  represents a moderate incentive level for analysis. The value-added service parameter and cost-benefit coefficient measure the depth of professional services provided by the park. Xi’an High-tech Zone’s establishment of proof-of-concept centers and pilot platforms embodies value-added service  $\delta$ , and setting  $\delta = 0.5$  represents a medium service level. The unit cost coefficient  $K = 20$  relative to the unit benefit  $T = 15$  reflects the real-world feature of increasing marginal costs in platform construction ( $K > T$ ). R&D efficiency and success rates capture the cooperative value. Existing literature generally recognizes that industry—university—research cooperation improves R&D success rates [46, 47]. Setting the cooperative R&D success rate  $p_1 = 0.9$  significantly higher than the independent R&D  $p_2 = 0.7$ , and R&D efficiency  $w_1 = 0.75$  higher than  $w_2 = 0.5$ , intuitively reflects the enabling effect of park services on the R&D process. The numerical simulation focuses on exploring how value-added service level, investment equity, subsidy ratio, and strategic returns in high-tech industrial parks influence the game system. For comparison purposes, initial probabilities are assumed to be (0.6, 0.6, 0.6).

### 5.1 Level impact of value-added service level: Information layer intensity and system stability interval

To analyze the impact of varying the level of value-added services  $\delta$  in high-tech industrial parks on the strategy choices of the game participants,  $\delta$  is set to 0.2, 0.5, and 0.7 while keeping all other parameters constant, as shown in Figure 2. Figure 2 indicates that, as the level of value-added services in the park increases, the stable strategies of the three participants evolve from (1, 0, 0) to (1, 1, 1) and then (0, 0, 0).

From a CPSS perspective,  $\delta$  represents the intensity of information support in the information layer. Its variation does not simply alter participants’ payoffs but changes the ability of the information layer to support physical R&D processes and social governance structures. When  $\delta$  is low ( $\delta = 0.2$ ), the digital platform’s information integration capability is limited, leading to high information asymmetry in the R&D process. The information layer cannot effectively support physical layer R&D activities, participants’ expectations of cooperation risk are high, and although the park may adopt active support behaviors, cross-participant collaboration struggles to form a stable structure. The system remains in a low-collaboration state. The core challenge at this stage lies in the weak information infrastructure, which places the system in a zone of high uncertainty and elevated collaboration risk, representing a typical CPSS security-vulnerable region. When  $\delta$  reaches a medium level ( $\delta = 0.5$ ), information flows provide effective support for R&D activities, uncertainty in the R&D process decreases, and a positive feedback mechanism aligned across the information, physical, and social layers emerges. The system enters a stable collaboration interval and converges to (1, 1, 1). From a CPSS perspective, when cross-layer coupling relationships within the R&D system are stable, the system enters a secure and governable stability interval, and collaborative R&D emerges as the evolutionarily advantageous strategy. However, when  $\delta$  further increases ( $\delta = 0.7$ ), the intensity of information layer investment exceeds the park’s sustainable input boundary. The cost pressure associated with high-level services disrupts the original

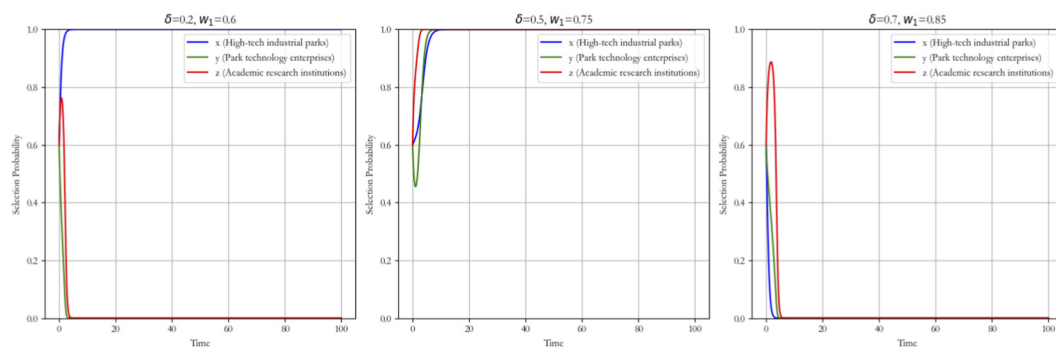


FIGURE 2  
Stability analysis of the game system in high-tech industrial parks under different value-added service levels.

payoff structure, strengthening decision constraints at the social layer and causing the park to adopt a passive support strategy. Inefficient investment in the information layer reduces physical layer R&D efficiency, weakens cooperation expectations at the social layer, and breaks the cross-layer feedback chain, ultimately causing the system to degrade to  $(0,0,0)$ . This result reveals that excessive digitalization also constitutes a governance risk in CPSS, fundamentally arising from structural instability caused when the expansion of the information layer exceeds the system's safety boundaries. Therefore, the variation of  $\delta$  demonstrates a typical system threshold effect: when information support intensity is within a moderate range, the system maintains stable collaboration from a CPSS perspective; when it falls below or exceeds the critical level, the system's stable structure cannot be sustained, exhibiting multistability and phase transition characteristics typical of non-equilibrium complex systems. This result highlights the issue of "safety boundary constraints" in digital infrastructure development, representing a typical governance challenge in CPSS.

## 5.2 Impact of investment share: Changes in resource allocation structure and cross-layer coupling strength

While keeping all other parameters constant, as shown in Figure 3 the investment share  $\alpha$  of the high-tech industrial park is set to 0.1, 0.3, and 0.6. Simulation results indicate that the system's stable state evolves along a path from  $(0,0,0)$  to  $(1,1,1)$  and then returns to a non-collaborative state as  $\alpha$  varies. From the CPSS perspective,  $\alpha$  reflects the park's depth of participation in physical layer R&D resource allocation and simultaneously affects the social layer's payoff distribution structure. When  $\alpha$  is low ( $\alpha = 0.1$ ), the park's R&D investment is insufficient, leaving physical layer R&D risks primarily to the enterprises. The social layer's payoff distribution fails to generate stable cooperation expectations, the system cannot establish a cross-layer positive feedback mechanism, and it ultimately converges to a non-cooperative equilibrium, at this stage, the risk manifests as insufficient provision of physical infrastructure, resulting in a lack of system safety redundancy. When  $\alpha$  increases to 0.3, the park's investment effectively alleviates enterprise R&D constraints, balancing resource allocation and payoff distribution. Decision support from the information layer,

R&D investment in the physical layer, and incentive mechanisms in the social layer interact synergistically, and the system enters a stable collaborative state, this indicates that moderate investment in the physical layer is a key condition for ensuring the stable operation of CPSS structures. However, when  $\alpha$  further rises to 0.6, the enterprise payoff space is excessively compressed, destabilizing the social layer's payoff structure. Enterprise R&D motivation declines, weakening physical layer operational efficiency. Due to inconsistent cross-layer feedback, system stability decreases and returns to a non-collaborative state. These results indicate that the investment share, as a control parameter, also has a stable interval. When it falls below or exceeds the critical level, the system's original equilibrium becomes unstable, reflecting the multistability and threshold regulation characteristics inherent in cyber-physical-social systems. This result indicates that excessive concentration of resource allocation can also trigger governance imbalances and collaboration safety risks. The findings further show that investment share, as a control parameter, has a stability range; when it falls below or exceeds the critical threshold, the system's original equilibrium becomes unstable, reflecting the multistability and threshold regulation characteristics of socio-physical systems.

## 5.3 Impact of subsidy ratio: social layer regulation strength and system disturbance risk

Shown in Figure 4 while keeping all other parameters constant, the subsidy ratio  $\phi$  represents the governance and regulatory intensity of the social layer. When the subsidy ratio is low ( $\phi = 0$ ), social layer incentives are insufficient, making it difficult for enterprises and academic research institutions to cover the additional risks of cooperative R&D. The system lacks the external driving force needed to form a collaborative structure, and it ultimately converges to a non-cooperative state. As the subsidy ratio increases to a moderate level, social layer regulation effectively lowers the threshold for cooperation, allowing the outcomes of the information and physical layers to translate into stable payoff expectations. Consequently, the system gradually enters a stable collaborative interval, this stage reflects the "stabilizer" function of social layer regulation on cross-layer coupling. However, when the subsidy ratio increases further ( $\phi = 0.4$ ), the intensity

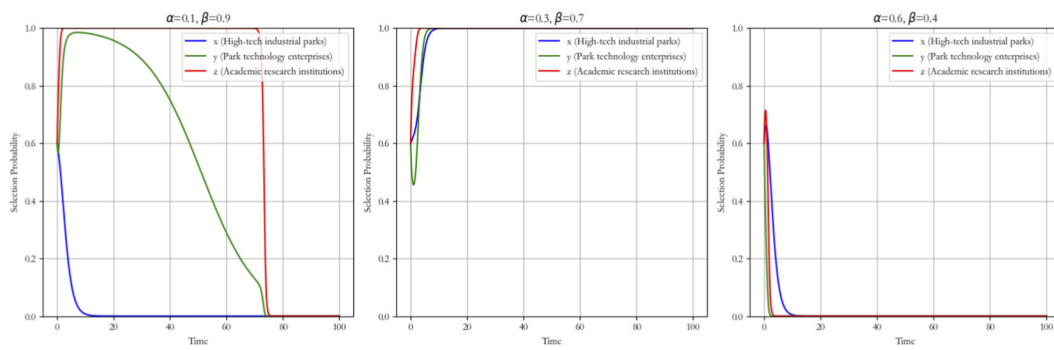


FIGURE 3 Stability analysis of the game system in high-tech industrial parks under different investment shareholding ratios.

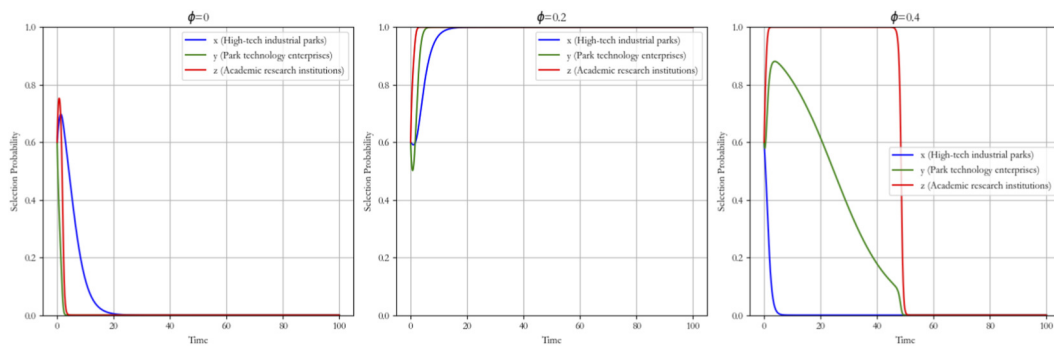


FIGURE 4 Stability analysis of the game system in high-tech industrial parks under different subsidy ratios.

of social layer intervention exceeds the system’s endogenous payoff level. Participants’ strategies begin to depend on external subsidies rather than R&D efficiency, causing a misalignment between information layer feedback and governance incentives. Excessive intervention distorts strategies, disrupts internal feedback mechanisms, and ultimately reduces system stability, causing it to revert to a non-cooperative equilibrium. Therefore, subsidy policies in CPSS systems have a dual effect: moderate intervention stabilizes the system, while excessive intervention introduces social layer disturbance risks and may trigger system instability. This result indicates that policy incentives have a dual effect—moderate intervention enhances system security, whereas excessive intervention creates risks of institutional dependence and governance disruption, representing a key safety challenge in the social layer governance of CPSS.

### 5.4 Impact of strategic payoff: system-level collaborative gains and stability threshold

Shown in Figure 5 while keeping all other parameters constant, the strategic payoff  $R_c^o$  is set to 10, 15, and 20. Simulation results indicate that, as strategic payoff increases, the system gradually evolves from a non-cooperative state to a stable collaborative equilibrium. From a CPSS perspective,  $R_c^o$  represents the system-

level collaborative gains emerging from the effective coupling of the information, physical, and social layers. When the strategic payoff is low, the combined gains from cross-layer collaboration are insufficient to offset the R&D risks borne by participants, making it difficult for the system to form a stable cooperative structure. This is reflected in a low-collaboration state. When  $R_c^o$  exceeds the critical threshold (set as 15 in this study), the system gains from collaborative R&D increase significantly, a cross-layer positive feedback mechanism is established, and the system transitions from a low-collaboration state to a high-collaboration stable state. This process demonstrates a typical phase transition behavior in non-equilibrium complex systems: the system does not change continuously, but undergoes a structural shift once a key parameter crosses the threshold. This process reflects the typical phase-transition behavior of non-equilibrium complex systems, where the system does not change continuously but undergoes a structural leap once a critical parameter crosses its threshold. This critical point essentially constitutes a “safety tipping point” for system governance.

Synthesizing the above results, it can be observed that the collaborative process of scientific and technological achievements research and development in high-tech industrial parks is not a linear accumulation process, but rather a nonlinear evolutionary system shaped by the joint interaction of the information, physical,

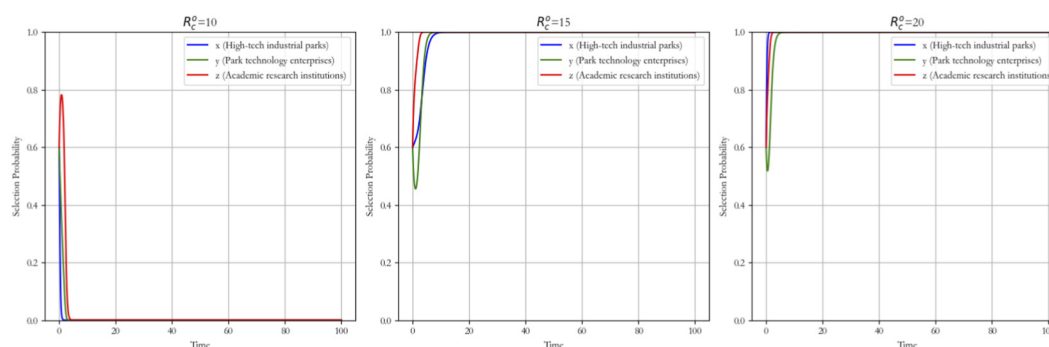


FIGURE 5  
Stability analysis of the game system in high-tech industrial parks under different strategic returns.

and social layers. Different control parameters affect the system's stability range by altering cross-layer coupling strength, giving rise to threshold effects, multistability coexistence, and equilibrium-state transitions—typical socio-physical system characteristics. Deviations from appropriate ranges can lead to the breaking of cross-layer feedback chains, imbalances in payoff structures, increased collaboration risks, and system regression from a collaborative state to a non-cooperative equilibrium. Integrating the above results, it can be observed that the collaborative R&D process of scientific and technological achievements in high-tech industrial parks is not a linearly cumulative process. Rather, it constitutes a nonlinear evolutionary system formed through the joint interactions of the information, physical, and social layers. Different control parameters influence the system's stability interval by altering the strength of cross-layer coupling, giving rise to threshold effects, multistability, and transitions between equilibrium states—typical characteristics of cyber-physical-social systems. From a CPSS perspective, key threshold effects and collaboration risks are not merely outcomes of the game but represent core governance and safety challenges within the system. Only when all critical parameters remain within reasonable ranges can the system achieve a stable transition from a low-coupling, disordered state to a high-coupling, ordered state, while maintaining structural security and long-term governability.

## 6 Conclusions and research limitations

### 6.1 Conclusions

High-tech industrial parks have become important spatial carriers and institutional innovation platforms for scientific and technological achievements research and development in China. The “administrative committee + enterprise” model, based on market-oriented operation, reshapes the governance structure of industrial parks through clear property rights, risk sharing, and benefit-sharing mechanisms, enabling industrial parks to gradually transform from traditional resource allocation platforms into organizational cores of innovation ecosystems. However, during the transition from factor agglomeration to collaborative innovation,

how institutional arrangements and resource allocation can promote industry—university—research actors to move from “physical coexistence” to “collaborative evolution” remains a key issue in the governance practice of high-tech industrial parks. Based on this background, from the perspective of social physics, this thesis embeds evolutionary game dynamics into the CPSS context, constructs a tripartite dynamic game model involving high-tech industrial parks, park technology enterprises, and academic research institutions under the “administrative committee + enterprise” model, and analyzes the influence mechanism of key parameters on system stability through replicator dynamic equations and numerical simulation. The main conclusions are as follows:

First, scientific and technological achievements research and development under the “administrative committee + enterprise” model is essentially a typical multi-actor collaborative evolutionary process from a CPSS perspective. High-tech industrial parks not only undertake the function of resource coordination within the system, but also connect the operational logic of the information, physical, and social layers through information platform construction and institutional arrangements. Park technology enterprises are responsible for implementing physical layer R&D activities and bearing technological and market risks, while academic research institutions sustain upstream innovation dynamics through knowledge supply and technology spillover. The strategy choices of the three parties are not independent decisions but form a dynamic adjustment process under cross-layer feedback. Simulation results indicate that whether the system converges to a collaborative equilibrium depends on the consistency of cross-layer coupling relationships. When information support, resource investment, and governance incentives generate positive feedback, the system evolves from a low-collaboration state to a stable collaborative structure.

Second, the formation of collaborative scientific and technological achievements research and development does not follow a linear input logic but exhibits significant threshold effects and multistability characteristics. Simulation results show that the effects of value-added service level, investment share ratio, and subsidy intensity all follow a nonlinear pattern in which effectiveness exists only within a moderate range, while values that are too low or too high lead to system instability. Among these factors, the value-added service level reflects the strength of information

layer support for the R&D process. When information support is insufficient, information asymmetry prevents the formation of stable cooperation expectations; when information investment exceeds the system's sustainable boundary, increased cost pressure weakens the foundation of collaboration. The investment share affects system stability by altering physical layer resource allocation and the social layer payoff distribution structure. Moderate participation helps establish a risk-sharing mechanism, whereas excessive shareholding compresses enterprise payoff space and weakens R&D incentives. The subsidy policy represents the governance and regulatory intensity of the social layer. Moderate subsidies reduce cooperation thresholds and promote the system's transition into a stable collaborative interval, while excessive intervention may cause strategy distortion and subsidy dependence, leading the system to revert to a non-cooperative equilibrium. These results indicate that the scientific and technological achievements research and development system in high-tech industrial parks constitutes a typical non-equilibrium complex system, whose stability depends on whether key control parameters remain within an appropriate range rather than on the continuous strengthening of any single factor.

Third, strategic payoff is the key incentive variable that drives the system to transition from a non-collaborative state to a collaborative equilibrium. When the system-level gains generated through cross-actor collaboration exceed a critical threshold, a stable positive feedback structure emerges among the information, physical, and social layers. Under such conditions, high-tech industrial parks tend to adopt an active support strategy and further strengthen collaborative relationships through equity investment, industrial funds, and service platform construction. In contrast, when collaborative gains are insufficient to offset R&D risks, park behavior becomes more conservative, and the system is unable to maintain a stable cooperative structure. This result indicates that collaborative gains are not a simple aggregation of individual actors' benefits, but rather systemic gains generated through cross-layer coupling within the CPSS framework.

Finally, and as an important extended conclusion of this thesis, from a CPSS perspective, the "administrative committee + enterprise" model provides important implications for the design of secure and governable CPSS architectures within innovation ecosystems. The results indicate that the stable operation of the scientific and technological achievements research and development system depends on three aspects. First, the information layer needs to maintain an appropriate level of information support intensity to reduce information asymmetry while avoiding the cost and governance risks caused by excessive platformization. Second, resource allocation in the physical layer should achieve a dynamic balance between risk sharing and benefit incentives through reasonable equity and investment structures, thereby ensuring the operational efficiency of the R&D system. Third, governance in the social layer should emphasize moderate intervention, maintaining endogenous system motivation through institutional rules rather than continuous subsidies. From the perspective of system design, security and governance are not external constraints but are embedded into the system's evolutionary process through cross-layer parameter regulation. When information flows, resources flow, and governance rules remain aligned in the same direction, the CPSS system can maintain structural stability and collaborative efficiency under uncertain environments. Conversely, excessive reinforcement

at any single layer may disrupt cross-layer feedback mechanisms and trigger systemic instability.

## 6.2 Research limitations and future directions

This thesis constructs an evolutionary game model to systematically analyze the cooperation mechanism and equilibrium conditions of scientific and technological achievements research and development in industrial parks under the "administrative committee + enterprise" model from a CPSS perspective. However, certain limitations remain in this study, which also indicate directions for future research.

1. This study focuses on the "administrative committee + enterprise," which integrates governmental governance attributes with market-oriented operational attributes. In essence, it represents a typical hybrid governance structure under the CPSS framework, where the social layer (policies and governance rules), the physical layer (R&D infrastructure and pilot testing platforms), and the information layer (digital platforms and data governance mechanisms) jointly form a composite incentive system. Compared with traditional government-led models or purely market-driven models, this structure incorporates both strategic ecological benefits and economic returns into its objective function, thereby facing more complex issues of incentive compatibility and governance coordination. The conclusions derived from the model—such as the threshold of strategic payoff and the balance relationship between equity structure and subsidy intensity—primarily reflect the internal logic of the coupled operation among the government, market, and technological system under the CPSS context. These findings provide references value for industrial parks with similar hybrid governance characteristics. However, in purely administrative or purely market-oriented scenarios with single objectives and lower levels of system coupling, their applicability still requires careful examination within specific institutional environments.
2. The gap between the simplifications adopted in the study and the real-world complexity of CPSS systems. To highlight the core game mechanism, this thesis introduces necessary abstractions of real CPSS systems. First, the model assumes relatively symmetric information, whereas in actual CPSS environments, significant differences exist among actors in data access capability, technological understanding, and policy interpretation. The incompleteness of the information layer may further influence the evolution of strategies by affecting trust formation and cooperation matching efficiency. Second, the model does not explicitly incorporate default penalties or dynamic regulatory mechanisms. In practical CPSS governance, digital supervision, contractual constraints, and performance evaluation often affect social layer decision-making through information layer feedback, thereby restraining opportunistic behavior. This thesis focuses on long-term strategic evolution rather than short-term contract enforcement, which, to some extent, limits the explanatory depth regarding cooperation breakdown risks and governance failure scenarios. In addition, some parameters (such as strategic payoff) remain theoretically abstract, and

their quantification still depends on calibration and validation based on real industrial park data in order to enhance the explanatory and predictive capability of the model in complex CPSS environments.

3. Impact of Regional and Industrial Heterogeneity on the operation of CPSS structures. The operational performance of CPSS systems is highly dependent on regional development conditions and industrial technological characteristics. Differences across regions in fiscal capacity, digital infrastructure, and the allocation of R&D resources directly influence the coupling strength among the information, physical, and social layers. For example, in regions with relatively limited fiscal capacity, governance priorities are more likely to focus on enhancing information service capability and improving innovation ecosystem quality to increase strategic payoff, rather than relying primarily on direct subsidies. In contrast, for industries such as biomedicine and high-end equipment manufacturing, which are characterized by long R&D cycles and high capital investment, the importance of physical layer infrastructure investment and risk-sharing mechanisms becomes more prominent. Overall, regional and industrial differences are mainly reflected in variations in the value ranges of key model parameters rather than in changes to the fundamental evolutionary logic. Future research may incorporate regional development level, industrial technological complexity, and the degree of digitalization as moderating variables, and conduct comparative static analysis or case studies to further deepen the understanding of model generalizability and contextual differences within CPSS environments.
4. CPSS extension directions for the model. Future research can further deepen the analysis in several directions. First, additional actors such as financial institutions, technology intermediaries, and digital platform operators can be incorporated into the framework to construct a more complete CPSS multi-actor game network, capturing cross-layer collaboration mechanisms within the innovation ecosystem. Second, dynamic parameters and stage-based evolutionary processes can be introduced to analyze the long-term effects of industrial policy cycles, technology maturation phases, and changes in data governance mechanisms on actors' strategies. Third, key parameters can be empirically calibrated using park financial data, cooperation contracts, and platform operation records to enhance the model's explanatory power in practice. Fourth, comparative studies across different governance models can be conducted, using counterfactual models to quantitatively assess how various governance structures affect collaborative efficiency and system stability in CPSS environments. Fifth, behavioral factors such as default penalties, dynamic regulation, and credit constraints can be incorporated into the game system to capture how information layer feedback regulates social layer governance and the stability of cooperation. Despite these limitations, this thesis, from an overall CPSS perspective, provides a theoretically grounded framework and analytical tools for understanding multi-actor collaboration mechanisms in scientific and technological achievements research and development under the "administrative committee + enterprise" model in high-tech industrial parks. Clearly defining the

study boundaries does not diminish its value; rather, it helps clarify the theoretical contributions and lays a foundation for future research addressing the complexities of real-world CPSS environments.

## Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

## Author contributions

MQ: Writing – original draft. HJ: Supervision, Writing – review and editing. MW: Writing – review and editing, Methodology, Formal Analysis. JW: Conceptualization, Writing – review and editing.

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## Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Generative AI statement

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