frontiers in Physics

TYPE Original Research
PUBLISHED 13 March 2026
DOI 10.3389/fphy.2026.1740603

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OPEN ACCESS

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RECEIVED 06 November 2025
REVISED 25 December 2025
ACCEPTED 30 January 2026
PUBLISHED 13 March 2026

CITATION
He Z, Ma X, Hu Y, Liu H and Dong X (2026) Dynamic evolution game of regional innovation ecosystem with multiple actors under digitalization. *Front. Phys.* 14:1740603. doi: 10.3389/fphy.2026.1740603

Dynamic evolution game of regional innovation ecosystem with multiple actors under digitalization

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Regional innovation ecosystems play a crucial role in advancing national innovation capacity. However, the question of how to foster sustained collaborative innovation among diverse actors within these ecosystems under digitalization remains underexplored. This study aims to investigate the dynamic mechanisms and key factors influencing synergistic innovation behavior among multiple stakeholders in digitally enabled regional innovation ecosystems. Drawing on evolutionary game theory, we develop a tripartite game model involving core enterprises, complementary parties, and the government. A simulation analysis is conducted using the Zhongguancun Science and Technology Park as a case context to examine the evolutionary trajectories of cooperation strategies. The results indicate that: (1) increasing the intensity of digital investment by innovation agents significantly enhances the stability and sustainability of the regional innovation ecosystem; (2) core enterprises can stimulate cooperative innovation by providing incentives to complementary parties in the digital context; (3) innovation actors exhibit substantial positive spillover effects, facilitating the circulation and integration of digital resources and data elements; and (4) government subsidies and penalties positively influence system stability and accelerate the convergence of evolutionary dynamics. By integrating a digital perspective into the analysis of regional innovation ecosystems, this study contributes to theoretical discussions on innovation cooperation and provides practical insights for local governments seeking to improve synergistic mechanisms within digital innovation ecosystems. The findings also offer strategic references for promoting the sustainable development of regional innovation systems under digitalization.

KEYWORDS
collaborative innovation, complementary parties, core enterprises, digitalization, evolutionary game theory

1 Introduction

Innovation is the primary driving force for development, and regional innovation is an important basis for supporting national innovation and development [1–3]. Currently, the regional innovative development model has evolved from a linear single model (innovation 1.0 stage) into an innovation system model (innovation 2.0 stage), and finally into an innovation ecosystem model (innovation 3.0 stage) [4, 5]. Systematic integration of innovation elements and enhancement of regional innovation ability has become the proposition of The Times [6]. At present, the development pattern of regional innovation space in China is still unbalanced [7]. Digital technology and data resources, as a new type of production factor, are rapidly gaining ground in regional innovation activities. Digital sharing, openness, value-adding, and applications are profoundly affecting and changing the way regions innovate. Digitalization is emerging as a key driver of regional innovation [8]. Silicon Valley generates 3% of U.S. GDP and 13% of U.S. patents with less than 1% of the population [9]. Silicon Valley's innovation ecosystem has the right kind of innovation environment that drives the healthy evolution of the entire regional innovation ecosystem.

The regional innovation ecosystem is the basic unit for the construction of the national innovation system. At the same time, it also undertakes the important task of creating innovative development regions [10].The regional innovation ecosystem is an open symbiotic system characterize by multiple subjects, multilateral relationships and multilevel structures [11]. In terms of system composition, the innovation ecosystem consists of subject species such as firms, universities, research institutes and government. They are interconnected and form various clusters. During the dynamic evolution of the system, heterogeneous species and clusters form competitive symbiotic relationships [12]. Regional innovation ecosystems emphases inter connectivity, structural integration and functional complementary between innovative species and related organization. Treat the region as a complex system as a whole. Apply the theory of complex systems to strengthen the coordinated development of interest-related subjects, complementary advantages, resource sharing, mutual benefits and synergies [13]. On this basis, a diversified, flexible and efficient innovation capital ecosystem will gradually be formed. Accelerate the transformation of system results and promote the formation of new productivity and new growth points. In turn, it will cultivate high-quality innovation subjects, promote the upgrading of the regional innovation ecosystem, and facilitate the high-quality development of the regional economy [14].

Regional innovation ecosystems under digitalization use digital technologies and data elements to create new products that connect participants at different levels of the system [15]. Digital technologies increase the degree of synergy between innovation actors and the degree of sharing between innovation resources [16, 17]. Digital technology facilitates green innovation in high-end equipment manufacturing systems [18]. In this paper, the regional innovation ecosystem under digitalization refers to an ecological organizational system in a certain spatial scope, in which the innovative subject creates new products, new technologies or new business models with the help of digital technology, and realizes value co-creation through competitive relationships [19]. It emphasizes that the participating subjects break through the time and space barriers and achieve value co-creation through cross-level resource complementation and sharing through digital technology [20].

In addition, some research scholars have conducted relevant studies on the evolutionary path of systemic innovation subjects based on the digital perspective. The study points out that government regulation, appropriate incentives, constraints, and innovation inputs, have a facilitating effect on the stability of systemic innovation agents. In the research on regional innovation ecosystems, evolutionary game theory has been widely employed by scholars to gain insights. Mahmoudi et al. (2018) constructed an evolutionary game model that considers the impact of subsidies and taxes on the performance of supply chain enterprises, the government and enterprises as the game subjects. Research has pointed out that judicious government taxation exerts a discernible effect on higher corporate performance [21]. Sun (2019) explored the evolutionary game problem between the government and shared digital platform management, suggesting that the government's actions towards reducing regulatory costs can propel the system towards a stable equilibrium state [22]. Fan et al. (2020) explored the impact of government incentives on the behavioral decisions of enterprise subjects based on evolutionary game theory. Their findings indicated that the interaction path between the two imposes an influence on the effectiveness of incentives [23]. Wang et al. (2019) constructed a game model of the evolution of value co-creation between focal and cooperative enterprises in innovation ecosystems. Their analysis revealed that factors such as the distribution ratio of excess benefits, cooperation cost, incentive and constraint mechanism, as well as punitive measures of focal and cooperative enterprises, collectively affect the stability of value co-creation behavior in regional innovation ecosystems [24]. Qi et al. (2013) constructed a tripartite evolutionary game model of regulators, enterprises and universities. Their study highlights that the costs and benefits of collaborative innovation stand as the key factors influencing the behavioral choices of innovation agents [25]. Zhu et al. (2016) further extended this paradigm, constructing a tripartite evolutionary game model with the government, enterprises, and universities as innovation subjects. Their findings indicate that the interplay of collaborative innovation benefits, costs, opportunistic gains, and government incentive and constraint mechanisms profoundly shape the evolutionary path of the subjects [26]. At the same time, if the governmental subjects within the innovation ecosystem directly consider their own benefits, it will reduce the stability of the system's industry-university-research collaborative innovation [27]. Existing studies have clarified the roles of core enterprises, governments and other system participants in the construction of innovation ecosystems [28]. Motivation for constructing or participating in the innovation ecosystem [29]. It lays the foundation for the research on the evolution mechanism of innovation subjects.

Research scholars have explored the theoretical construction of innovation ecosystems under digitalization, governance mechanisms [30], research frameworks [31], symbiosis models [32], and factors affecting the innovation efficiency of core enterprises [33]. And existing studies have not yet analysed in depth the interaction and synergy mechanisms between the main bodies of regional innovation ecosystems under digitalization. Moreover, most of the existing research is based on case studies and theoretical analyses, but it lacks strong mathematical and theoretical validation of the interaction and synergy mechanisms between innovation agents in the ecosystem. Existing research provides a solid theoretical foundation for the article, but there is still room for expansion: Firstly, the widespread use of digital technology has disrupted the traditional mode of production. Secondly, due to the self-growth and convergence of digital innovation [34], the evolutionary game simulation model helps to explore the value co-creation behaviour of multiple subjects in the digital innovation ecosystem in the long-term repetitive game to make strategic choices, and gradually reach a stable and dynamic convergence process after many repetitive games.

In order to fill these gaps in the literature, the main innovation of this paper is:to use evolutionary game theory to conduct an in-depth study of the dynamic evolutionary game of innovation subjects in regional innovation ecosystems under digitalization. On this basis, a tripartite game model is constructed with core enterprises, complementary parties and the government as the three types of subjects. This paper analyses the symbiotic evolution process and equilibrium state of innovation subjects of regional innovation ecosystem under digitalization through computer simulation. And take the regional innovation ecosystem under digitalisation in Zhongguancun, China, as an example for validation analysis, to explore the evolution mechanism and path to promote the reciprocal symbiosis of the innovation ecosystem.It provides a realistic basis for the sustainable and healthy development of regional innovation ecosystem.

The rest of this article is organized as follows. In Section 2, we introduce the construction of evolutionary game model. In Section 3, we explore the stability analysis of evolutionary strategy. The model of innovation ecosystem in Zhongguancun region is simulated and analyzed in Section 4. In Section 5, we describe the research conclusions. The management implication of this study is proposed in Section 6. We illustrate the shortcomings and future prospects of this study in Section 7.

2 Evolutionary game model construction

2.1 Evolutionary game logic deduction

In the digital context, the regional innovation ecosystem is no longer confined to time and space constraints [35], but relies on digital technology, key complementary resources, knowledge sharing platforms and knowledge-driven innovation to restructure existing innovation resources and processes to realize the connection and interaction of the innovation ecosystem. In this paper, the regional innovation ecosystem under digitalization is defined as an innovation subject in order to cope with various external risks and challenges in the innovation process, with digital technology as the link and digital platform as the support, and three types of subjects consisting of core enterprises (high-tech supporters), complementary parties (universities, research institutions, financial service intermediaries and other complementary innovation resources), and government as the constituent elements [36]. The synergistic evolution of innovation subjects maximizes the synergistic benefits of each party, forming a complex interactive network system for dynamic and sustainable development [37]. Based on the above research, the logical relationship between the three evolving game subjects of regional innovation ecosystem constructed in this paper is shown in Figure 1.

2.2 Model variables and assumptions

The regional innovation ecosystem is a complex network structure with enterprises as the main body and universities, scientific research institutions, government, finance and other intermediary service institutions as the carriers of system elements. Through inter-organizational network collaboration, the system forms industrial alliances between subjects, deeply integrates human, technology, information, capital and other innovation factors, realizes effective convergence of innovation factors, brings value creation to each subject in the system, and realizes sustainable development of each subject. In the evolutionary game model constructed in this study, there are three types of participants: core enterprises, complementary parties and government. In the innovation ecosystem, they play different roles in the ecosystem and have their own unique innovation resources, and there is a competition and cooperation relationship among them. In order to achieve the goal of collaborative innovation, innovation agents need to go through the process of constantly adjusting their behavioral strategies and repeatedly playing games, which fully reflects the theoretical significance of evolutionary games. Based on the above, this paper proposes the following four hypotheses from the perspective of sustainability, combining the “cost-benefit” model and evolutionary game theory:

*Hypothesis*1: Participating Subjects. Without considering other constraints, the core enterprises, complementary parties and the government constitute a complete system, and all three subjects are finite rational individuals who have their own criteria and rights for behavior selection. In the development process of regional innovation ecosystem under digitalization, core enterprises are mainly responsible for technological innovation resources required for technology *R&D* and promoting high-quality transformation of technological achievements; complementary parties are mainly responsible for providing technical talents, innovation knowledge, front-end information, investment and financing costs required for technology *R&D*; the government mainly provides business environment guarantee for joint *R&D* of core enterprises and complementary parties to promote collaborative high-quality development.

*Hypothesis*2: Participation strategy. In the process of collaborative innovation evolution of regional innovation ecosystem, the behavioral decision set of core enterprises is collaborative, non-collaborative, the probability of choosing collaborative decision is x $(0 \le x \le 1)$, the probability of choosing non-collaborative decision is $(1 - x)$; the behavioral decision set of complementary parties is collaborative, non-collaborative, the probability of choosing collaborative decision is $y(0 \le y \le 1)$, the probability of choosing non-collaborative decision is $(1 - y)$; The set of behavioral strategies of the government sector is supporting, not supporting, the probability of choosing the supporting decision is $z(0 \le z \le 1)$, and the probability of choosing the not supporting decision is $(1 - z)$. During the evolutionary process, the three populations kept repeating experiments and strategy selection to seek evolutionarily stable strategies (ESS).

*Hypothesis*3: Game gain. When innovative subjects are choosing a collaborative innovation strategy, they can receive innovation subsidies from the government. When one of the subjects chooses to default, then the defaulting party will be liable for penalties. Synergistic enterprises have characteristics such as openness, ecology, and collaboration. Enterprises connect and interact with other entities through digital technology in areas such as data

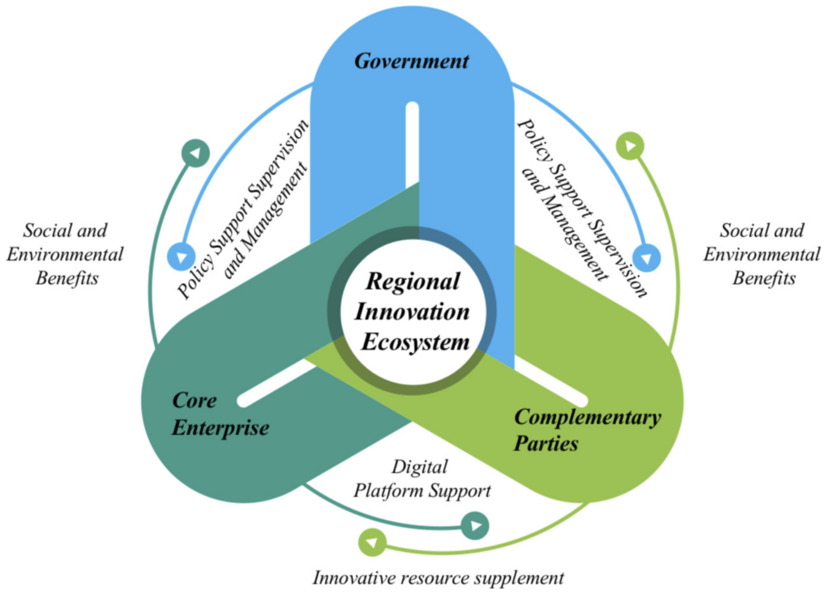

FIGURE 1
Logical deduction of the tripartite game model.

sharing, technological cooperation, and interoperability of network resources. Non Synergistic enterprises have characteristics such as independence. Enterprises choose to conduct independent technological innovation within the organization. In a regional innovation ecosystem under digitalization, the traditional benefits are W_A and W_B for the core enterprise and the complementary parties when they choose not to collaborate, and R_A and R_B for the core enterprise and the complementary parties when they each innovate digitally; considering the leading position of the core enterprises in the regional innovation ecosystem, the ratio of the benefits for the core enterprises and the complementary parties when they collaborate is bound to be different. The coefficient of distribution of the benefits obtained by the core enterprise from collaborative innovation is α, the coefficient of distribution of the benefits obtained by the complementary party is $(1-\alpha)$, and the coefficient of benefits from collaborative innovation is β. In the digital era, digital technology has greatly reduced the cost of interaction between enterprises and enterprises and between enterprises and users, making the organizational boundaries increasingly blurred, increasing user participation, and the competition and complementarity of different technologies can help enterprises to find ecological objects to meet the diversified needs of users more quickly. At the same time, the innovation ecosystem's self-evolution has been strengthened by enterprise-led collaborative innovation among industries, universities and research institutes, as well as collaborative innovation with the participation of multiple stakeholders. The government's input costs such as innovation subsidies for collaborative innovation with the core enterprise and the complementary parties are H. The social and environmental benefits obtained by the government when it chooses the support strategy are W_G; when the core enterprise and the complementary party respectively engage in collaborative innovation, the benefits to the government are $L_A$and L_B.

*Hypothesis*4: Game cost. When the system innovators carry out diversified cooperative behaviors such as industry-university-research collaborative innovation, joint laboratories and investment and financing trading platforms, the core enterprises can realize collaborative innovation by building new channels to pool new resources. When the core enterprise collaborates with the complementary parties, the *R&D* cost is K_A. When the complementary parties collaborates with the core enterprise, it needs to support talents, information, knowledge and capital, and the *R&D* input cost of the complementary party is K_B. When the innovation subjects cooperate in collaborative innovation, the spillover coefficients of digital technology of the core enterprise and the complementary parties are μ_A and μ_B respectively, and the default amount to be paid for betraying the contract is E. The government imposes a penalty on the core enterprise and the complementary parties for betraying the contract. The government imposes a fine of F on both the core enterprise and the complementary party for breach of contract." Before carrying out a synergistic project, the government will agree on the rights and obligations of both parties and the distribution of benefits in the form of a written agreement. At the same time, it will improve the default mechanism of the two synergistic parties as a way to guarantee the smooth conduct of synergistic innovation strategy.

2.3 Model construction

2.3.1 Payment matrix construction

The core enterprises, the complementary parties and the government constitute the complete system, and all three subjects are finite rational individuals who have their own criteria and rights for behavioral choices. The assumptions discussed earlier suggest that in the development of regional innovation ecosystems

TABLE 1 Tripartite game revenue matrix for government support.

		Complementary parties B Synergistic (y)	Non synergistic ($1-y$)
Core enterprise A	Synergistic (x)	$W_A+\alpha\beta R_A-K_A+H-T_A$	$W_A-K_A+H-T_A+E$
		$W_B+\beta(1-\alpha)R_B-K_B+H+T_A$	$W_B+\mu_A R_A+T_A-F-E$
		$W_G+L_A+L_B-2H$	W_G+F+L_A-H
	Non synergistic ($1-x$)	$W_A+\mu_B R_B-F-E$	W_A-F
		W_B-K_B+H+E	W_B-F
		W_G+F+L_B-H	W_G+2F

TABLE 2 The revenue matrix of the tripartite game without government support.

		Complementary parties B Synergistic (y)	Non synergistic ($1-y$)
Core enterprise A	Synergistic (x)	$W_A+\alpha\beta R_A-K_A-T_A$	$W_A-K_A-T_A+E$
		$W_B+\beta(1-\alpha)R_B-K_B+T_A$	$W_B+\mu_A R_A+T_A-E$
		L_A+L_B	L_A
	Non synergistic ($1-x$)	$W_A+\mu_B R_B-E$	W_A
		W_B-K_B+E	W_B
		L_B	0

under digitalization, core enterprises will provide digital technology development resources, and compartmentalizes will pay the factor costs of digital technology knowledge, information and talents. And the government provides the business environment guarantee for the core enterprises and the complementary parties to jointly research and develop. Referring to the related literature [38, 39], this paper discusses and analyses based on the theoretical foundation of game theory and using the evolutionary game model. According to the above research hypotheses, the payoff matrix of the evolutionary game with the core enterprise A, the complementary parties B and the government as the three parties is constructed, as shown in Tables 1, 2.

2.3.2 Symbol definition

Based on the above research driving and model construction, this study gives the meaning of model symbols. The notation about the payoff matrix is shown in Table 3.

3 Evolutionary strategy stability analysis

3.1 Analysis of the evolutionary stabilization strategy of each party subject

3.1.1 Game equilibrium analysis of core enterprises

The expected return when the core enterprises are synergistic is e_A^1, the expected return when they are not synergistic is e_A^2, and the average expected return is $\overline{e_A}$. Then, the specific calculation formula can be obtained as follows as shown in Equations 1–3:

$$\begin{aligned} e_A^1 &= yz(W_A+\alpha\beta R_A-K_A+H-T_A)+y(1-z)(W_A+\alpha\beta R_A-K_A-T_A)\\ &\quad+(1-y)z(W_A-K_A+H-T_A+E)\\ &\quad+(1-y)(1-z)(W_A-K_A-T_A+E) \end{aligned} \tag{1}$$

$$\begin{aligned} e_A^2 &= yz\left(W_A+\mu_B R_B-F-E\right)+y(1-z)\left(W_A+\mu_B R_B-E\right)\\ &\quad+(1-y)z(W_A-F)+(1-y)(1-z)W_A \end{aligned} \tag{2}$$

$$\overline{e_A} = xe_A^1+(1-x)e_A^2 \tag{3}$$

The replication dynamic equation for the core enterprises is as shown in Equation 4:

$$\begin{aligned} F(x) &= \frac{dx}{dt} = x\left(e_A^1-\overline{e_A}\right) = x(1-x)\left(e_A^1-e_A^2\right)\\ &= x(1-x)\left[K_A-E+T_A-z(F+H)+y\left(\mu_B R_B-\alpha\beta R_A\right)\right] \end{aligned} \tag{4}$$

The following is the process of determining the strategy choice of the core enterprises through the law of determination in order to analyze the strategy choice of the game subjects:

The derivative of $F(x)$ yields

$$\frac{dF(x)}{dx} = (1-2x)\left[K_A-E+T_A-z(F+H)+y\left(\mu_B R_B-\alpha\beta R_A\right)\right] \tag{5}$$

1. When $y^* = \frac{E+z(F+H)-K_A-T_A}{\mu_B R_B-\alpha\beta R_A}$, $F(x)\equiv 0$, it can be concluded that the system can reach a steady state at this time regardless of the value of x. That is, when the probability of complementary parties choosing to collaborate reaches y^*, the initial ratio of the probability of core enterprises choosing to synergistic with the probability of non synergistic is stable.

10.3389/fphy.2026.1740603

TABLE 3 **Model symbols.**

Symbols	Meaning	Range
W_A	Traditional benefits from autonomous innovation in core enterprises	
	Of regional innovation ecosystems	
W_B	Traditional benefits arising from autonomous innovation by complementary	
	Parties in regional innovation ecosystems	
W_G	Social and environmental benefits arising from government's choice of enabling policies	
R_A	Synergistic innovation benefits gained when core enterprises engage in co-innovation	
R_B	Synergistic innovation benefits gained when complementary parties engage in co-innovation	
L_A	Governments gain synergistic benefits when core enterprises innovate synergistically	
L_B	Governments gain synergistic benefits when complementary party innovate synergistically	
α	Coefficient of distribution of gains from synergistic innovation	$0 \le \alpha \le 1$
β	Coefficient of effectiveness of synergistic innovation	$0 \le \beta \le 1$
K_A	Costs invested by core enterprises when both sides engage in synergistic innovation	
K_B	Costs invested by complementary party when both sides engage in synergistic innovation	
μ_A	Digital technology spillover factor for core enterprises	$0 \le \mu_A \le 1$
μ_B	Digital technology spillover factor for complementary parties	$0 \le \mu_B \le 1$
E	Amount of liquidated damages for breach of contract	
H	Government subsidies for synergy innovation	
T_A	The core enterprises will give complementary parties certain incentive inputs in order to	
	Encourage them to synergistic with each other	
F	Government fines for betrayal of contracts by core enterprises or complementary parties	

2. When $y^* = \frac{E+z(F+H)-K_A-T_A}{\mu_B R_B-\alpha\beta R_A}$, $\frac{dF(x)}{dx}|_{x=0} < 0$, $\frac{dF(x)}{dx}|_{x=1} > 0$, at this time $x = 0$ is the evolutionary stable strategy of the system *ESS*, which indicates that at this time the probability of synergistic of complementary parties is greater, and the synergistic benefit reaches the highest. At this time the core enterprises for in the complementary party positive synergistic strategy will choose the non synergistic strategy.
3. When $y^* = \frac{E+z(F+H)-K_A-T_A}{\mu_B R_B-\alpha\beta R_A}$, $\frac{dF(x)}{dx}|_{x=0} > 0$, $\frac{dF(x)}{dx}|_{x=1} < 0$, at this time $x = 1$ is the evolutionary stable strategy of the system *ESS*, which indicates that at this time the probability of complementary parties synergy is small and the synergistic benefit reaches the minimum. At this time, the core enterprises will choose the synergistic strategy and incentivize the complementary party in order to seek the maximization of its own interests under the complementary party's choice of non synergistic strategy.

3.1.2 Game equilibrium analysis of complementary parties

The expected gain when the complementary parties are synergistic is e_B^1, the expected gain when they are no synergy is e_B^2, and the average expected gain is $\overline{e_B}$. Then, the specific calculation formula can be obtained as follows as shown in Equations 6–8:

$$e_B^1 = xz\left[W_B + \beta(1-\alpha)R_B - K_B + H + T_A\right] + x(1-z)\left[W_B + \beta(1-\alpha)R_B - K_B + T_A\right] + (1-x)z(W_B - K_B + H + E) + (1-x)(1-z)(W_B - K_B + E) \tag{6}$$

$$e_B^2 = xz\left(W_B + \mu_A R_A + T_A - F - E\right) + x(1-z)\left(W_B + \mu_A R_A + T_A - E\right) + (1-x)z(W_B - F) + (1-x)(1-z)W_B \tag{7}$$

$$\overline{e_B} = ye_B^1 + (1-y)e_B^2 \tag{8}$$

The replicated dynamic equation for the complementary parties is as shown in Equation 9:

$$F(y) = \frac{dy}{dt} = y\left(e_B^1 - \overline{e_B}\right) = y(1-y)\left(e_B^1 - e_B^2\right) = y(1-y)\left[K_B - x\left(\beta R_B - \mu_A R_A + \alpha\beta R_A\right) - z(F+H) - E\right] \tag{9}$$

The following is the process of determining the strategy choice of the Complementary parties through the law of determination in order to analyze the strategy choice of the game subjects:

The derivative of $F(y)$ yields

$$\frac{dF(y)}{dy} = (1-2y)\left[K_B - x\left(\beta R_B - \mu_A R_A + \alpha\beta R_A\right) - z(F+H) - E\right] \tag{10}$$

1. When $Z^* = \frac{K_B-E-x(\beta R_B-\mu_A R_A-\alpha\beta R_A)}{F+H}$, $F(y) \equiv 0$, it can be concluded that at this time, no matter what value y takes the system

 10.3389/fphy.2026.1740603

can reach a steady state, that is, the initial proportion of complementary parties choosing synergistic and non-synergistic probabilities is stable when the probability of the government choosing an enabling strategy is reached.

2. When $Z > Z^* = \frac{K_B - E - x(\beta R_B - \mu_A R_A - \alpha\beta R_A)}{F+H}$, $\frac{dF(y)}{dy}\big|_{y=0} > 0$, $\frac{dF(y)}{dy}\big|_{y=1} < 0$, at this time $y = 1$ is the evolutionary stable strategy of the system *ESS*, which indicates that at this time the complementary parties have a higher probability of choosing the strategy of synergistic strategy, and at this time the government's strategy choice under the synergistic strategy of the complementary parties is not supportive.
3. When $Z < Z^* = \frac{K_B - E - x(\beta R_B - \mu_A R_A - \alpha\beta R_A)}{F+H}$, $\frac{dF(y)}{dy}\big|_{y=0} < 0$, $\frac{dF(y)}{dy}\big|_{y=1} > 0$, at this time $y = 0$ is the evolutionary stable strategy of the system *ESS*, which indicates that at this time the complementary party has a higher probability of choosing the strategy of non-synergistic strategy, and at this time the government's strategy choice under the non synergistic strategy of the complementary party is enabling.

3.1.3 Game equilibrium analysis of the government

The expected return when the government supports is e_G^1, the expected return when it does not support is e_G^2, and the average expected return is $\overline{e_G}$. Then, the specific calculation formula can be obtained as follows as shown in Equations 11–13:

$$e_G^1 = xy(W_G + L_A + L_B - 2H) + y(1-x)(W_G + F + L_B - H) + x(1-y)(W_G + F + L_A - H) + (1-x)(1-y)(W_G + 2F) \quad (11)$$

$$e_G^2 = xy(L_A + L_B) + y(1-x)(L_B) + (1-x)(1-y)0 \quad (12)$$

$$\overline{e_G} = ze_G^1 + (1-z)e_G^2 \quad (13)$$

The replication dynamics equation for the government is as shown in Equation 14:

$$\begin{aligned} F(z) = \frac{dz}{dt} &= z(e_G^1 - \overline{e_G}) = z(1-z)(e_G^1 - e_G^2) \\ &= z(1-z)[x(F+H) + y(F+H) - W_G - 2F] \end{aligned} \quad (14)$$

The rule of judgment is used to analyze the strategy choice of the game subjects, and the following is the process of determining the government's strategy choice:

The derivative of $F(z)$ yields:

$$\frac{dF(z)}{dz} = (1-2z)[x(F+H) + y(F+H) - W_G - 2F] \quad (15)$$

1. When $y^* = \frac{2F + W_G - x(F+H)}{F+H}$, $F(z) \equiv 0$, it can be concluded that the system can reach a stable state at this time regardless of the value of y. That is, when the probability of the strategy of the complementary party choosing synergy reaches y^*, the initial proportion of the probability of the strategy of government subjects choosing to support and not to support is stable.
2. When $y > y^* = \frac{2F + W_G - x(F+H)}{F+H}$, $\frac{dF(z)}{dz}\big|_{z=0} > 0$, $\frac{dF(z)}{dz}\big|_{z=1} < 0$, at this time $z = 1$ is the evolutionary stability strategy of the system *ESS*. This indicates that at this time, when the probability of non-synergistic strategies of complementary parties is higher, governmental agents will engage in enabling strategies to drive to achieve a healthy and good sustainable development of the system.
3. When $y < y^* = \frac{2F + W_G - x(F+H)}{F+H}$, $\frac{dF(z)}{dz}\big|_{z=0} < 0$, $\frac{dF(z)}{dz}\big|_{z=1} > 0$, when $z = 0$ is the evolutionary stability strategy of the system *ESS*. This indicates that at this time, when the probability of the complementary parties choosing the synergistic strategy is higher, the governmental agent will perform non-supportive and instead exercise external supervision of the ecosystem to ensure the maximization of the governmental agent's own interests.

3.2 Analysis of the overall system evolutionary stabilization strategy

Associating Equations 5, 10, 15, the system of replication dynamic equations constituting the multi-subject synergistic of the regional innovation ecosystem based on the triad of core enterprises, complementary parties, and government is as shown in Equation 16:

$$\begin{cases} \frac{dx}{dt} = x(1-x)[K_A - E + T_A - z(F+H) + y(\mu_B R_B - \alpha\beta R_A)] \\ \frac{dy}{dt} = y(1-y)[K_B - x(\beta R_B - \mu_A R_A + \alpha\beta R_A) - z(F+H) - E] \\ \frac{dz}{dt} = z(1-z)[x(F+H) + y(F+H) - W_G - 2F] \end{cases} \quad (16)$$

Let $F(x) = 0$, $F(y) = 0$, $F(z) = 0$ to find the equilibrium point of the system.Ritzberger and Weibull (1996) point out that for a system consisting of three parties [40, 41], the core enterprise, the complementary party and the government, only the stable points $E_1(0,0,0)$, $E_2(1,0,0)$, $E_3(0,1,0)$, $E_4(0,0,1)$, $E_5(1,1,0)$, $E_6(1,0,1)$, $E_7(0,1,1)$, $E_8(1,1,1)$, $E_1(0,0,0)$ to $E_8(1,1,1)$ are pure strategic Nash equilibrium solutions of the evolutionary game, and the remaining points are non-asymptotic steady states. We can obtain the Jacobi matrix of the tripartite game system as follows as shown in Equation 17:

$$J = \begin{bmatrix} J_1 & J_2 & J_3 \\ J_4 & J_5 & J_6 \\ J_7 & J_8 & J_9 \end{bmatrix} = \begin{bmatrix} \frac{dF(x)}{dx} & \frac{dF(x)}{dy} & \frac{dF(x)}{dz} \\ \frac{dF(y)}{dx} & \frac{dF(y)}{dy} & \frac{dF(y)}{dz} \\ \frac{dF(z)}{dx} & \frac{dF(z)}{dy} & \frac{dF(z)}{dz} \end{bmatrix}$$

$$= \begin{bmatrix} (2x-1)(E - K_A - T_A + zF + zH - \mu_B R_B y + \alpha\beta R_A y) & x(1-x)(\mu_B R_B - \alpha\beta R_A) & x(x-1)(F+H) \\ y(1-y)(\mu_A R_A - \beta R_B + \alpha\beta R_B) & (2y-1)(E - K_B + zF + zH + \beta R_B x - \mu_A R_A x - \alpha\beta R_B x) & y(y-1)(F+H) \\ z(1-z)(F+H) & z(1-z)(F+H) & (1-2z)(xF - W_G - 2F + Fy + Hx + Hy) \end{bmatrix} \quad (17)$$

3.3 Equilibrium point stability analysis

First, the equilibrium point $E_1(0,0,0)$ is used as an example for judgment, and the Jacobi matrix J_1 at this point is as shown in Equation 18:

$$J_1 = \begin{bmatrix} K_A - E + T_A & 0 & 0 \\ 0 & K_B - E & 0 \\ 0 & 0 & -2F - W_G \end{bmatrix} \quad (18)$$

TABLE 4 Eigenvalues of Jacobi matrix.

Equilibriumpoint	Eigenvalue λ_1	Eigenvalue λ_2	Eigenvalue λ_3
$E_1(0,0,0)$	$K_A - E + T_A$	$K_B - E$	$-(2F + W_G)$
$E_2(1,0,0)$	$-(K_A - E + T_A)$	$K_B - E - \beta R_B + \mu_A R_A + \alpha\beta R_B$	$H - F - W_G$
$E_3(0,1,0)$	$K_A - E + T_A + \mu_B R_B - \alpha\beta R_A$	$-(K_B - E)$	$H - F - W_G$
$E_4(0,0,1)$	$K_A - F - H - E + T_A$	$K_B - F - H - E$	$2F + W_G$
$E_5(1,1,0)$	$-(K_A - E + T_A + \mu_B R_B - \alpha\beta R_A)$	$-(K_B - E - \beta R_B + \mu_A R_A + \alpha\beta R_B)$	$2H - W_G$
$E_6(1,0,1)$	$-(K_A - F - H - E + T_A)$	$K_B - F - H - E - \beta R_B + \mu_A R_A + \alpha\beta R_B$	$-(H - F - W_G)$
$E_7(0,1,1)$	$K_A - F - H - E + T_A + \mu_B R_B - \alpha\beta R_A$	$-(K_B - F - H - E)$	$-(H - F - W_G)$
$E_8(1,1,1)$	$-(K_A - F - H - E + T_A + \mu_B R_B - \alpha\beta R_A)$	$-(K_B - F - H - E - \beta R_B + \mu_A R_A + \alpha\beta R_B)$	$-(2H - W_G)$

TABLE 5 Eigenvalue sign of Jacobi matrix and stability analysis.

Equilibrium point	Eigenvalue λ_1	Eigenvalue λ_2	Eigenvalue λ_3	Stability
$E_1(0,0,0)$	−	+	−	Unstable point
$E_2(1,0,0)$	−	+	−	Unstable point
$E_3(0,1,0)$	+	−	−	Unstable point
$E_4(0,0,1)$	−	+	+	Unstable point
$E_5(1,1,0)$	−	−	−	Stability point (ESS)
$E_6(1,0,1)$	−	+	+	Unstable point
$E_7(0,1,1)$	+	−	+	Unstable point
$E_8(1,1,1)$	−	−	+	Unstable point

The eigenvalues $\lambda_1 = K_A - E + T_A$; $\lambda_2 = K_B - E$; $\lambda_3 = -2F - W_G$ of the Jacobi matrix of point E_1 are derived from J_1. If the eigenvalues are all negative, it means that the equilibrium point is a stable point of the evolutionary game. $\lambda_1 = K_A - E + T_A$ is always positive, so $E_1(0,0,0)$ is an unstable point. Based on the above analysis, the remaining eight equilibrium points are substituted into the Jacobi matrix (14) in turn, and the eigenvalues of the Jacobi matrix corresponding to the eight equilibrium points are obtained, as shown in Table 4.

According to the evolutionary game theory and Lyapunov's first method (indirect method), if all the eigenvalues of the Jacobi matrix are negative when any equilibrium is substituted into the Jacobi matrix, the equilibrium is an asymptotically stable point and the system will eventually be in a stable state. If at least one of the eigenvalues of the Jacobi matrix is positive, the equilibrium is an unstable point and the system will be in an unstable state. To facilitate the analysis of the sign of the eigenvalues of the Jacobi matrix corresponding to different equilibrium points without loss of generality, let $K_A - E + T_A > 0$, i.e., the sum of the input cost of the core enterprise to carry out synergistic innovation and the incentive cost given to encourage the complementary parties to synergistic is greater than the amount of default to be paid when each party betrays the contract. Based on the above research results, the stability of the eigenvalues of the Jacobi matrix is determined, as shown in Table 5.

According to the above analysis, it can be seen that when $K_A - E + T_A + \mu_B R_B - \alpha\beta R_A > 0$ and $K_B - E - \beta R_B + \mu_A R_A + \alpha\beta R_B > 0$, the eigenvalues corresponding to the equilibrium point are all negative, and the system is in a stable state. Under the above conditions, the evolutionary game phase diagram of the system is shown in Figure 2. That is, the regional innovation ecosystem is in the E5(1,1,0) stable state when the core enterprises choose synergistic, the complementary parties choose synergistic, and the government chooses non-supportive strategy.

4 Simulation analysis of zhongguancun regional innovation ecosystem model

4.1 Example selection and simulation parameter setting

To validate the effectiveness and real-world explanatory power of the theoretical model, this study selects the Beijing Zhongguancun Science Park as the case object for simulation analysis. This choice is primarily based on Zhongguancun's outstanding typicality, maturity, and referential value within the context of digital regional innovation ecosystems, which is reflected in the following three aspects: First, institutional and policy pioneering. Zhongguancun is China's first national innovation demonstration zone, having long served as a "testing ground" for science and technology system reform and innovation policies. The coordinated governance model of

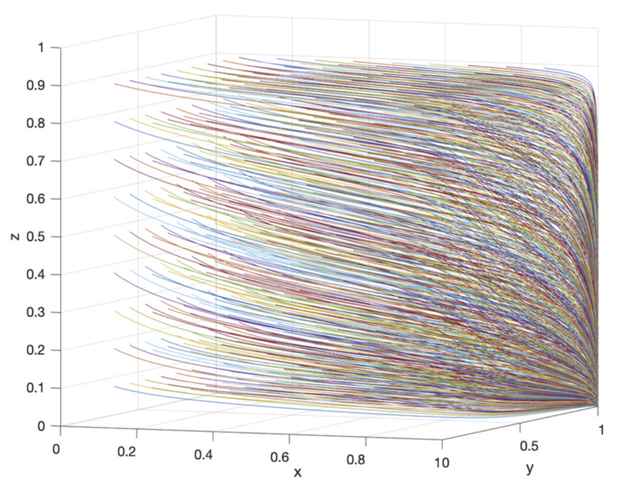

FIGURE 2
Phase diagram of the evolutionary game between core enterprise, complementary parties and government.

"government guidance, market leadership, enterprise protagonism, and platform support" that has emerged there represents a microcosm of the evolution of China's regional innovation systems. It provides an institutional background template for studying the tripartite interaction among "core enterprises, complementary parties, and the government." Second, maturity of the digital platform and structural congruence.Zhongguancun early on established digital collaboration systems such as the "Zhongguancun E-Innovation Service Platform," enabling the online integration and intelligent matching of innovation actors, resources, and processes. Within this platform ecosystem, high-tech enterprises as the core enterprises, universities/research institutes and financial institutions as the complementary parties, and government departments providing policies and regulation collectively form a clear tripartite actor structure. This aligns closely with the evolutionary game model constructed in this paper. Third, significant innovation performance and observable spillover effects. Zhongguancun has formed internationally competitive innovation clusters in fields such as artificial intelligence and integrated circuits. The mechanisms governing internal knowledge flow, technology spillover, and collaborative benefit distribution are relatively transparent and have been extensively studied. This provides a realistic basis and data reference for assigning values to key parameters in our model, such as collaborative benefits and spillover coefficients. In summary, the Zhongguancun case is not only representative at the phenomenological level, but its internal structure and operational mechanisms also provide a suitable "laboratory" for testing the theoretical model proposed in this study. The simulation analysis based on this case contributes to enhancing the real-world explanatory power of the research conclusions and the generalizability of the managerial insights.

Based on the stability analysis of the innovation subjects in the digital regional innovation ecosystem mentioned above, in order to more intuitively demonstrate the evolution process and laws of the symbiotic game, this paper uses MATLAB 2016 simulation software to conduct a system dynamics analysis of the evolution game of the innovation subjects in the digital regional innovation ecosystem. On the basis of considering the construction behavior of collaborative and symbiotic relationships between enterprises in reality, this article refers to relevant scientific and technological reports, consults experts in enterprise innovation research, and draws on relevant papers to preliminarily assign parameters.

The parameter values in this article are based on the actual operational data and related research of the Zhongguancun Information Valley Collaborative Innovation Platform. This article sets RA = 10 and RB = 8, based on the profit distribution ratio between Zhongguancun core enterprises and complementary parties in collaborative innovation; F = 0.5, E = 1, H = 0.5, This reflects the actual subsidy and punishment intensity of the government in the region.

In this paper, Zhongguancun Science Park Collaborative Innovation Platform (ZGC Information Valley) in the regional innovation ecology of ZGC Science Park is selected as the simulation object, and sensitivity analysis is conducted.The raw data of this paper mainly comes from Beijing Statistical Yearbook, ZGC Statistical Yearbook and ZGC related research reports. Meanwhile, relevant literature is referred to [42]. This paper adopts the methods of systematic interviews and participant observation to review the research and interview data of the top management of ZGC Science and Technology Park Administrative Committee and the management of ZGC Science Park Collaborative Innovation Platform. On this basis, the parameter allocation was carried out (Unit: 10,000 CNY), and we gave the initial values of the parameters of the evolutionary game model, as shown in Table 6.

With the help of Matlab-R2022a software, we simulate the strategy evolution process of the three parties, namely, core enterprise, complementary parties and government, under different innovation benefits, cost costs and governance strategy. And based on this, we explore the effective governance mechanism to promote the sustainable development of regional innovation ecosystem.

4.2 Discussion

4.2.1 The evolutionary impact of digital input cost intensity on system innovation

According to Figure 3, the evolutionary simulation of the core enterprises paying different cost costs when carrying out collaborative innovation is carried out by setting $K_A = 3$, $K_A = 5$ and $K_A = 7$ on the basis of the base model, and the willingness of the three parties is 0.4, 0.5 and 0.6, respectively. It can be seen that as the cost of synergistic input of core enterprises increases, the evolutionary convergence of the system to the stable point $E_5(1,1,0)$ gradually accelerates, making the time for the system to reach the stable state gradually becomes smaller. Therefore, the probability of core enterprises choosing synergistic strategy gradually tends to one and the speed is accelerated; according to Figure 3, on the basis of the basic model, we set $K_B = 3$, $K_B = 5$ and $K_B = 7$, and the willingness of three parties is 0.4, 0.5 and 0.6, respectively, to simulate the evolution of different cost costs paid by complementary parties when they carry out synergistic innovation. It can be seen that the evolutionary convergence of the system to the stable point $E_5(1,1,0)$ gradually accelerates as the cost of synergistic input of complementary parties increases, making the time for the system

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TABLE 6 **Parameter initialization setting table.**

R_A	R_B	K_A	K_B	W_G	T_A	F	E	H	α	β	μ_A	μ_B
10.00	8.00	5.00	2.50	2.00	0.21	0.50	1.00	0.50	0.56	0.36	0.34	0.34

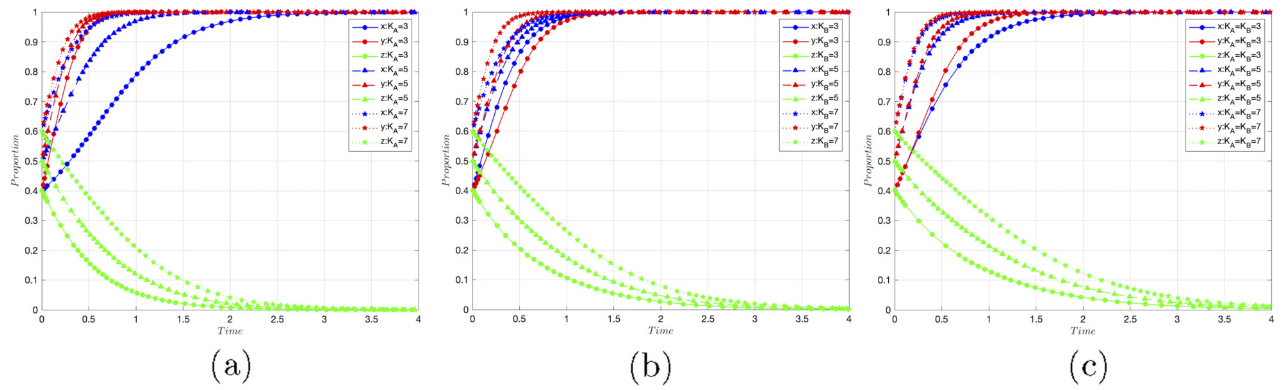

FIGURE 3
Dynamic evolution of digital input costs of innovation agents on system synergy **(a)** Single variable (core business input costs) **(b)** Single variable (complementary party input costs) **(c)** Multiple variables (joint input costs for both parties).

to reach the stable state gradually become smaller. Therefore, the probability of the complementary parties choosing the synergistic strategy gradually converges to one and accelerates; according to Figure 3, we set $K_A = K_B = 3$, $K_A = K_B = 5$ and $K_A = K_B = 7$ respectively, and the willingness of the three parties is 0.4, 0.5 and 0.6 respectively, and simulate the evolution of each party putting in different synergistic innovation costs at the same time. It can be seen that as the input cost of each party increases, the convergence speed of the system to the stable point $E_5(1,1,0)$ is gradually accelerated, which makes the time to reach the stable state gradually become smaller. At the same time, the synergistic correlation between the core enterprise and the complementary parties becomes closer, which makes the synergistic cooperation more stable. Based on Figure 3, it can be seen that as the cost of synergistic inputs of core enterprises increases, the government's evolution towards the stabilization point slows down the rate of convergence, which shows that the regional innovation ecosystem has the characteristics of self-organization, and with the evolution of time, the government has shifted from a direct dominant role to an indirect tutelage, and the benefits of synergistic innovations are owned by both the core enterprises and the complementary parties.

Based on market and technology connections, the network connections among innovation agents within the Zhongguancun regional innovation ecosystem are complex and diverse, which makes its evolutionary process dynamic [42]. When the input cost of both parties is set to 3, the digital platform of the Zhongguancun regional innovation ecosystem begins to be constructed. Core enterprises start to implement informatization based on digital technologies, and the construction of digital infrastructure, led by digital technologies such as OA and ERP, informatizes the internal management of the region. At this time, interactions between core enterprises and complementary parties (represented by universities and research institutions) in the service platform are relatively scarce. Therefore, core enterprises implement incentive mechanisms for complementary parties with the goal to stimulate these complementary parties to carry out collaborative innovation with the core enterprises to increase the innovation revenue. When the input cost is set to 5, the Zhongguancun regional innovation ecosystem relies on the digital platform to integrate and expand heterogeneous digital resources. Consequently, these resources can be updated from traditional distributed and decentralized resources to digital resources with the characteristics of autonomy, interconnection, aggregation, timeliness, and storability. When the input cost is set to 7, the Zhongguancun collaborative innovation service platform forms a relatively scientific and perfect digital platform. At the same time, the platform develops a national information standardization process, gradually leading the ecological construction of international science and technology parks. Core enterprises realize the linkage of innovation subjects through the platform, and the benefits of collaborative innovation of all parties begin to increase significantly. Consequently, platforms such as the Internet industry alliance, the national technology transfer center, and a high-tech industry base are forming. At this time, while strengthening incentives and constraints for original core enterprises and complementary parties, benign competition among the new emerging subjects that flood the platform is promoted. Governmental strategy changes from a supporting governance strategy to guaranteeing the healthy operation of the service platform, thus enhancing the overall competitiveness of the ecosystem.

Both “strengthening incentive and constraint mechanisms” and “supporting governance strategies to ensure the healthy operation of service platforms” are effective measures to establish a well functioning regional innovation ecosystem. The two complement each other, forming a strong support for the stable evolution of regional innovation ecosystems under digitization. In the early stage of regional innovation ecosystem growth, the government takes the lead in building regional innovation platforms, gathering innovation subjects and factors, and optimizing the innovation environment. With the evolution of time, in the growth and maturity of the regional innovation ecosystem, the government's direct orientation and supportive policies will be gradually activated and shifted to the government's indirect services and support. At this time, the government focuses on guaranteeing the healthy and good operation of the digital platforms in the regional innovation ecosystem, to create an innovation environment conducive to innovation.

4.2.2 The evolutionary impact of core enterprise incentive inputs on systemic innovation

According to Figure 4, the evolutionary simulation of the core enterprise inputting different incentive costs is carried out on the basis of the base model by setting $T_A = 0.5$, $T_A = 1$ and $T_A = 1.5$, and the three-party willingness is 0.4, 0.5 and 0.6, respectively. It can be seen that, as the incentive input from the core enterprise to the complementary party increases, the system converges to the stable point $E_5(1,1,0)$ gradually, the time to reach the stable state gradually becomes smaller, and the probability of the complementary party choosing the synergistic strategy gradually tends to one and the speed increases. It can be seen that with increasing incentive input, the convergence speed of core enterprises choosing synergistic gradually accelerates, as does the convergence speed of complementary parties choosing synergistic. Under the strategy of no support, the government guides complementary parties (such as universities and research institutions) to form the interaction mode of equity incentives with core enterprises. Examples are equity in scientific and technological achievements, discounted shares of scientific and technological achievements, equity rewards, equity sale, and share of proceeds of scientific and technological achievements. The incentive mechanism can be used to stimulate the willingness of complementary parties to collaborate and innovate, which is a necessary prerequisite for complementary parties to participate in the innovation ecosystem [43].

4.2.3 The evolutionary impact of innovation spillovers on systemic innovation

As shown in Figure 5, based on the baseline model and with the initial willingness levels of the three parties set at 0.4, 0.5, and 0.6, respectively, simulations were conducted by setting the core enterprise's innovation spillover coefficient to $\mu_A = 0.3$, 0.6, and 0.9. The results indicate that as the core enterprise's innovation spillover coefficient increases, the system's convergence speed toward the stable point (1, 1, 0) gradually accelerates, and the time required to reach a stable state decreases. Furthermore, the probability of both the core enterprise and complementary parties choosing the collaborative strategy increasingly approaches 1, with a faster convergence rate. According to Figure 5, simulations were performed by varying the complementary party's innovation spillover coefficient ($\mu_B = 0.3$, 0.6, 0.9) under the same baseline model and initial willingness settings. It can be observed that as the complementary party's innovation spillover coefficient increases, the system converges more rapidly to the stable point (1, 1, 0), and the time to stability is reduced. Based on Figure 5, simulations were carried out by simultaneously increasing the innovation spillover coefficients of both parties ($\mu_A = \mu_B = 0.3$, 0.6, 0.9). The results demonstrate that as the innovation spillover coefficients of both entities increase, the system's convergence speed toward the stable point (1, 1, 0) accelerates, and the time to stability diminishes. Simultaneously, the cooperative relationship between the core enterprise and complementary parties becomes tighter, leading to more stable collaboration. This indicates that an increase in the innovation spillover coefficients of all parties accelerates the convergence of the regional innovation ecosystem toward its equilibrium. The innovation spillover effect is prominently reflected in the interactive behaviors between enterprises and universities or research institutions. A positive correlation exists between the number of enterprise patent applications and the spillover from academic research activities. As an intellectual and technology-intensive high-tech industrial cluster, Zhongguancun relies on universities and research institutions such as the Chinese Academy of Sciences, Peking University, Tsinghua University, national engineering centers, and key laboratories. Benefiting significantly from the knowledge spillover effects of these complementary parties, core enterprises generate more original innovations and achieve technological breakthroughs. Concurrently, driven by digitalization, Zhongguancun has established the Zhongguancun Information Valley Collaborative Innovation Platform, attracting multinational corporations and experimental centers to join. This platform breaks the spatial and temporal constraints on the interaction of knowledge, information, and technology, providing core enterprises with access to globally advanced technologies. The innovation radiation from core enterprises, in turn, drives universities and research institutions to engage in new technology development, highlighting the innovation spillover effects. At this stage, a strong linkage forms between product innovation at the back end of the innovation chain and knowledge innovation at the front end, thereby promoting the sustainable development of collaborative innovation within the regional innovation ecosystem.

4.2.4 The evolutionary impact of government regulation on systemic innovation

As shown in Figure 6, based on the baseline model and with the willingness levels of the three parties set at 0.4, 0.5, and 0.6 respectively, simulations were conducted by setting the government's subsidy amount to $H = 0.1$, $H = 0.5$, and $H = 1$ to examine the impact of varying subsidy policies. The results show that as the government increases its innovation subsidies to all parties, the system converges more rapidly toward the stable point $E_5(1,1,0)$, and the time required to reach a stable state decreases. According to Figure 6, similar simulations were performed by varying the penalty amount ($F = 0.1$, 0.5, 1) while holding other parameters and initial willingness levels constant. It can be observed that as the government raises the financial penalties imposed on the parties, the system's convergence speed toward $E_5(1,1,0)$ also accelerates, leading to a shorter time to stability.

From Figure 6, it can be concluded that the intensity of government incentives and penalties is positively correlated with the stability of the digital-enabled regional innovation ecosystem. Both subsidy-only and penalty-only policies can effectively drive the core enterprise and complementary parties to adopt collaborative strategies in digital technology *R&D*. Furthermore, Figure 6 demonstrates that both subsidy input and penalty amount are

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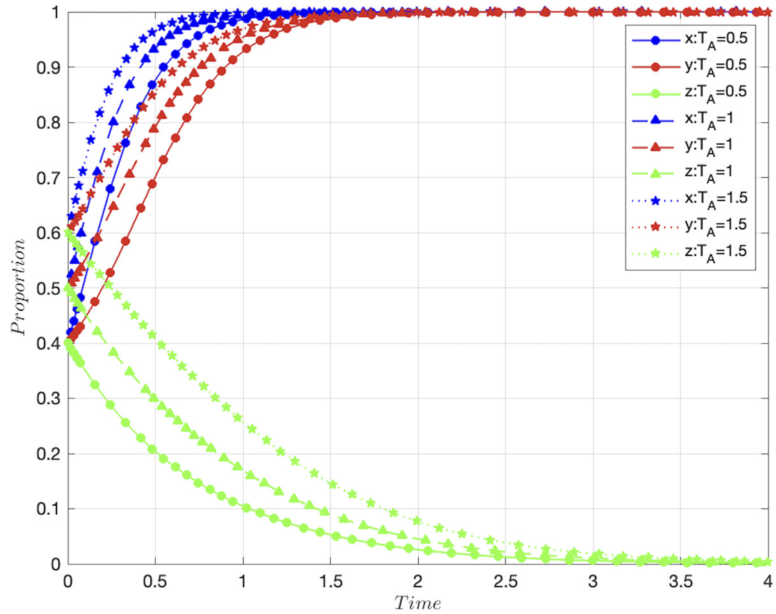

FIGURE 4
Dynamic evolution of system synergistic with different incentive inputs from core enterprise.

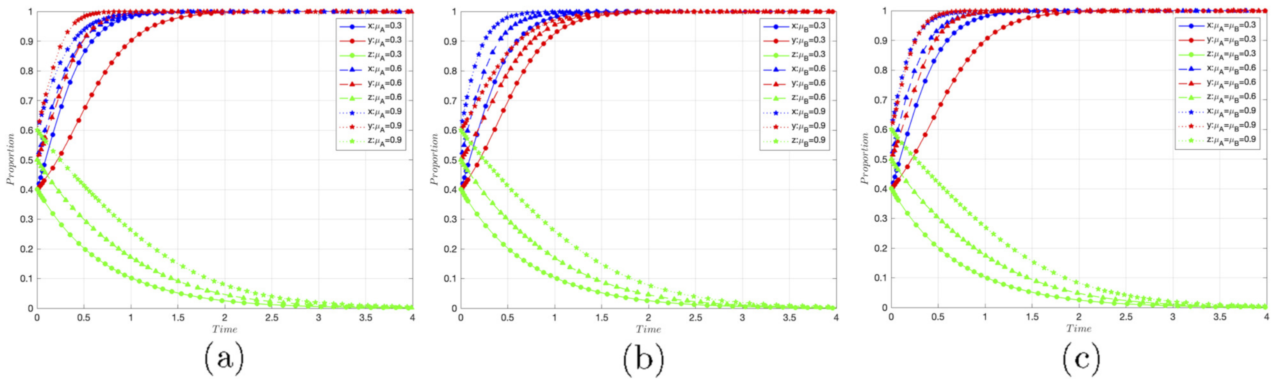

FIGURE 5
Dynamic evolution of spillover effects on system synergistic **(a)** Single variable (innovation spillover from core enterprise) **(b)** Single variable (complementary party innovation spillover) **(c)** Multiple variables (innovation spillover from both sides).

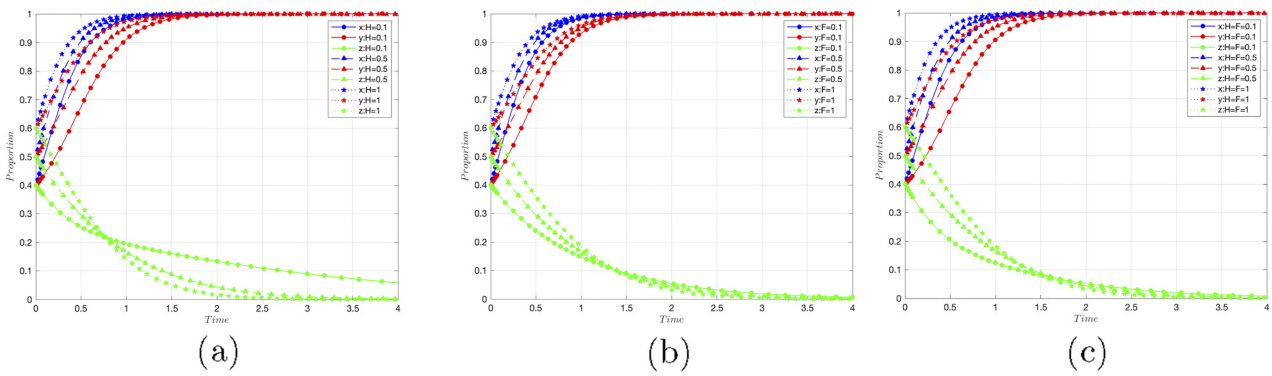

FIGURE 6
Dynamic evolution of the synergistic between different government innovation subsidies and fines on the system **(a)** Single variable (subsidy) **(b)** Single variable (penalty) **(c)** Multiple variables (subsidies and penalties).

positively associated with the stability of the Zhongguancun regional innovation ecosystem. A well-supervised reward-punishment mechanism can foster a relatively stable collaborative pattern between the core enterprise and complementary parties. When government subsidies are strengthened, the incentive mechanism effectively promotes industry-university-research collaboration, mitigates short-term fluctuations during the collaborative process, and helps achieve a local equilibrium within the innovation ecosystem [44]. In the initial stage of ecosystem agglomeration, the government provides support to all actors, ensuring that the ecosystem enters a sustainable development track. As the ecosystem matures and stabilizes, the government's intervention gradually decreases, ultimately shifting from a proactive "front-stage" supporting role to a more restrained "backstage" supervisory role. At this point, because the proportion of collaborative cooperation between the core enterprise and complementary parties continues to rise and their incremental benefits exceed the costs, the system attains a relatively stable state. This reflects the government's evolving role in economic development—akin to "helping to mount the horse and accompanying for part of the journey" [45] —which is also consistent with the actual trajectory of Zhongguancun Science Park, where early government leadership transitioned to later-stage oversight.

5 Conclusion

Using evolutionary game theory, in this paper, a tripartite evolutionary game model is constructed that is based on core enterprises, complementary parties, and the government. This model embeds a sustainable value logic system of synergistic innovation. With it, the nonlinear strategy roles of core enterprises, complementary parties, and the government can be analyzed in the process of synergistic innovation in the regional innovation ecosystem under digitalization. On this basis, a simulation analysis of the regional innovation ecosystem in Zhongguancun is conducted to disclose the evolutionary trajectory of tripartite strategies under different input intensities, incentive inputs, innovation spillover effects, and governmental regulation contexts. The following main conclusions are drawn:

1. Based on the nonlinear interactions of the evolutionary game, the behavioral strategy of the synergistic relationship between all parties in the regional innovation ecosystem under digitalization is sustainable along the evolutionary path containing core enterprise synergy, complementary party synergy, and governmental non-support. In this system, when the sum of the input cost of the core enterprise for synergistic innovation and the incentive cost for encouraging complementary parties to synergistic exceeds the cost of breach of contract when each party betrays the contract, the core enterprise and the complementary parties will have high expectations of the benefits of synergistic innovation in the synergistic cooperation. Thus, the stable and sustainable development of the system can be realized.
2. With increasing input cost of core enterprises and complementary parties for synergistic innovation, the stability of interaction and synergistic of all parties in the evolution of the regional innovation ecosystem gradually increases. Consequently, the system converges faster to the stability point (1,1,0). With the gradual improvement of the digital platform, core enterprises start the information construction and digital transformation; at this stage, the core enterprises mainly implement incentive mechanisms for the complementary parties to stimulate both parties and to realize the synergistic innovation cooperation mode. Consequently, the stable and sustainable development of the ecosystem can be achieved.
3. The more core enterprises implement incentives to complementary parties, the closer the synergistic innovation cooperation relationship between core enterprises and complementary parties, and the faster the system converges to the stability point (1,1,0). Core enterprises adopt incentives to increase the incremental benefits of the participation of complementary parties in synergistic innovation and to promote the proactive participation of complementary parties in the sharing of innovation resources. At the same time, the core enterprise and the complementary party sign a collaborative innovation contract in which they agree on the variable benefits to be given to the complementary party in the cooperation agreement.
4. The higher the innovation spillover coefficient between core enterprises and complementary parties, the closer the synergistic innovation cooperation relationship between them, and the faster the system converges to the stability point (1,1,0). The regional innovation ecosystem has open characteristics, which mainly manifest in the exchange of resources, information, and technology among various subjects in the system. The regional innovation ecosystem generates clear innovation spillover effects. According to the simulation results, the innovation ability of each type of subject is significantly affected by the positive spillover effect provided by other subjects in the same time and space. This indicates that a closer synergistic innovation relationship has been formed among the three subjects in the Zhongguancun regional innovation ecosystem.
5. Under governmental participation in regulation, governmental subsidies and penalties are positively correlated with the stability of the regional innovation ecosystem under digitalization. The simultaneous effect of subsidies and penalties accelerates the convergence rate of the innovation ecosystem compared to a single subsidy or penalty mechanism. At the same time, governmental governance and regulatory actions can effectively manage the positive spillover effects between core enterprise and complementary parties. These actions can also prompt the parties to maintain long-term effective synergistic innovation technology development.

The contributions of this study compared to previous studies are as follows: By comparing with the literature [22], this paper applies evolutionary game theory to construct a tripartite game model model based on core enterprise, complementary parties and the government. Meanwhile, embedded in the sustainable value logic system of collaborative innovation, this paper analyses the non-linear behaviour roles of core enterprises, complementary parties and government in the collaborative innovation process of regional innovation ecosystems under digitalization. Based on related literature [37], this paper introduces complex system theory based on the general framework of digital innovation ecosystem. At the same time, evolutionary game theory is applied to simulate and analyse the ZGC regional innovation ecosystem. The evolutionary trajectories of tripartite strategies under different input intensities, incentive inputs, innovation spillover effects and government regulation scenarios are revealed.

ZGC Information Valley promotes the deep integration of digital technologies such as the Internet, big data and artificial intelligence with the real economy. To form digital emerging formats such as fin-tech, smart logistics, autonomous driving, new retail, and sharing economy.In 2019, the total revenue of ZGC's digital economy was 3.01 trillion CNY, accounting for 45.3% of ZGC's total revenue and an increase of 18.3% compared to 2018. ZGC Information Valley has gradually become one of the most resource intensive and innovative regions in China's digital economy (Data source: Yearbook of Zhongguancun 2020). Based on this, ZGC Information Valley is in a leading position in key areas such as artificial intelligence, big data, and integrated circuits.

Therefore, this study has the following important theoretical and practical implications. First, based on evolutionary game theory, this paper constructs a three-party evolutionary game model of core enterprises, complementary parties and government in regional innovation ecosystem. Secondly, this paper simulates the multi-body synergy of ZGC regional innovation ecosystem. It explores the dynamic decision-making process and key factors of the collaborative innovation behaviour of core enterprises, complementary parties and the government. Thirdly, this paper introduces digitalization theory to reshape the cooperation of collaborative innovation between system innovation subjects. This paper expands the existing theoretical boundaries of regional innovation ecosystem and provides a theoretical basis for the improvement of regional innovation efficiency.

The simulation results above indicate that as the collaborative input cost increases, the system's convergence speed toward a stable equilibrium actually accelerates. This seemingly counterintuitive phenomenon can be explained through the incentive structure of evolutionary game theory and the dynamic adaptability of innovation ecosystems:

1. Cost as a Commitment Signal and Cooperative Credibility.In evolutionary games, higher collaborative costs often imply stronger resource commitments by actors to the cooperative endeavor. Such commitments can serve as credible signals of collaboration. When core enterprises or complementary parties invest higher costs, the price of exiting cooperation rises correspondingly, thereby reducing incentives for opportunistic behavior and enhancing the credibility and sustainability of cooperation.
2. Benefit–Cost Ratio and the Dynamics of System Convergence.In our model, collaborative innovation benefits and spillover effects are not isolated from costs; in real systems, higher costs are often associated with higher expected collaborative benefits or stronger absorptive capacity for spillovers. When actors anticipate that the net collaborative benefit (benefit minus cost) remains positive and significant, higher costs can instead accelerate their evolution toward a collaborative strategy because the opportunity cost of not cooperating increases accordingly.
3. Niche Lock-in and Path Dependency Effects.In regional innovation ecosystems, high-cost investments often lead to increased resource specificity and structural embeddedness, resulting in a niche lock-in effect. Once actors choose to collaborate and commit high costs, their flexibility to adjust strategies diminishes, and the system as a whole moves more rapidly toward a collaborative equilibrium, manifesting as accelerated evolutionary convergence.
4. The Role of Government and Cost Compensation Mechanisms.Although the government does not provide direct subsidies at equilibrium in our model, in a high-cost collaborative environment, the government can indirectly reduce cooperation risks and enhance actors' willingness to engage in high-cost collaboration through institutional safeguards and platform co-construction, thereby accelerating system convergence.

Therefore, "increased cost accelerates convergence" does not imply that cost itself promotes collaboration. Rather, under the benefit structure, spillover mechanisms, and governmental oversight defined in this study, high costs act as strong commitment signals and specialized investments, reinforcing cooperative stability and thereby driving the system more rapidly toward a collaborative equilibrium. This mechanism aligns with empirical observations in mature innovation ecosystems such as Zhongguancun, where actors establish long-term cooperative relationships through substantial investments.

6 Managerial implications

Based on the research results presented above, this paper proposes the following policy recommendations to promote the synergy of innovation agents and realize the sustainable development of the regional innovation ecosystem under digitization. These recommendations are based on the three subjects of core enterprises, complementary parties, and the government, and the roles assumed by these three subjects in the system are taken as the starting point:

Core enterprises should gradually replace the government and take up the important responsibility of designing the ecosystem architecture and sustaining the collaborative innovation of innovation subjects. The empowerment of digital technology and data elements should be relied on to build a diversified digital innovation service platform and continuously explore value innovation opportunities that move the system away from the equilibrium state [46]. Further, new demand discovery, new market development, and new system synergy should be gradually realized. Second, core enterprises and the government should adopt incentive mechanisms for complementary parties to optimize the openness of the system boundary [47], while gradually expanding the heterogeneous resources of complementary parties and increasing the willingness of each party to collaborate in innovation. Third, core enterprises should establish a synergistic innovation mechanism to enhance the network effect with complementary parties [45]. A resource sharing mechanism should be established to enhance the synergistic innovation benefits of each party. A risk sharing mechanism should be established to reduce the risk level in the process of the transformation of scientific and technological achievements of each party, to realize the stability and sustainability of the innovation ecosystem.

Complementary parties should actively supplement heterogeneous innovation resources in the ecosystem. Cooperative *R&D* is a change process that is intertwined with adaptive organizational learning [48]. As time evolves, the degree of digital integration within the system and the ability to collaborate on knowledge has a profound impact on digital supply chain collaboration [49]. Under governmental supervision, core enterprises and complementary parties (such as various universities, research institutions, and financial intermediaries) build shared information digital platforms, open laboratories, and technology consulting companies to carry out science and technology achievement transformation activities. The innovation achievements of various subjects in the system spill over to each other through various channels and continue to penetrate and spread to promote the continuous upgrading of the regional innovation system. In the digital context, an "active + active" interaction is formed among innovation subjects, which in turn promotes the complementation of innovation resources among subjects.

Universities and research institutions face the real problem of disconnection between the transformation of scientific and technological achievements and the market. In the process of contact with core enterprises, complementary parties shift from their traditional closed *R&D* thinking to targeted innovation and services based on the needs of enterprises. Thus, the trust of enterprises is gradually won while adapting to the rhythm of their needs. Then, enterprises become able to play an important role in the *R&D* process of certain core technologies or modules such as basic research, special technology research, and product trial production [50]. In turn, the sustainable development of the regional innovation ecosystem can be achieved.

Finally, the government should fully utilize its facilitating role in the ecosystem. First, at the early stage of the development of a regional innovation ecosystem under digitalization, the government guides the region to build a healthy and good business environment through a series of relevant policy supports. The willingness of synergistic innovation between core enterprises and complementary parties should be enhanced, and the sustainable development of the innovation ecosystem should be driven to achieve improved social and environmental benefits. Second, governmental subsidies and penalty mechanisms should be improved to help synergistic collaborative innovation achieve stability and sustainability. However, governmental subsidies and punishment mechanisms should be balanced to overcome the dependence of core enterprises and complementary parties on government support policies. Third, based on the principle of complementary advantages and resource sharing, the government should actively build an industry-university-research collaborative innovation platform to overcome both institutional and geographical barriers in the flow of talents, capital, and information (as well as other factors). Doing so can realize a new pattern of synergistic innovation development in the region that evolves from a point to a line, and then gradually promoting it.

7 Future outlook

Because of the limitations of models and simulations, they do not fully respond to complex and changing specific situations in reality. In this paper, the collaborative evolution paths and synergistic innovation mechanisms of innovation subjects within regional innovation ecosystems under digitalization are analyzed from the perspective of theoretical models. While several conclusions could be drawn, certain enhancements can still be made: (1) The focus of this paper is mainly on the synergistic innovation cooperation strategy of core enterprises, complementary parties, and the government. The role of other innovation subjects such as users has not been examined. (2) Different regional innovation ecosystems differ in terms of costs, benefits, and policies of relevant subjects in different business areas; therefore, the game benefit matrices of innovation ecosystems in different business areas as well as game strategies are different. (3)In the context of digitalization, different innovation subjects within the regional innovation ecosystem engage in different degrees of digital empowerment during the evolutionary game. Therefore, is there a difference between the degree of digital empowerment of innovation subjects and the choice of gaming strategies. In this regard, further thinking is needed.

In the future, the exploration of the synergistic evolutionary game mechanism of regional innovation ecosystem should be continued focusing on the following two aspects: (1) Users should be incorporated into the game model, and the evolutionary game of the four parties in the regional innovation ecosystem under digitalization should be explored. (2) An evolutionary game simulation analysis for regional innovation ecosystems with different attributes should be conducted. Further, a comparative analysis of simulations for two types of innovation ecosystems with different attributes should also be conducted. At the same time, the fit between the theoretical model and the actual governance environment should be improved to increase the effectiveness of the governance strategy. (3)Digital empowerment is included as a new parameter in the multi-party game model of regional innovation ecosystems under digitalization. Different situations are discussed and analysed differently.

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

ZH: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review and editing. XM: Data curation, Methodology, Supervision, Writing – original draft, Writing – review and editing. YH: Conceptualization, Data curation, Software, Writing – review and editing. HL: Data curation, Funding acquisition, Project administration, Writing – review and editing. XD: Data curation, Project administration, Software, Supervision, Writing – review and editing.

Funding

The author(s) declared that financial support was received for this work and/or its publication. The author acknowledges funding received from the following science foundations: Project on Economic and Social Development in Liaoning Province (2026lslybkt-043), Basic Research Project for Higher Education Institutions of Liaoning Provincial Department of Education (LJKZR20220039), Liaoning Provincial Science Public Welfare Research Fund (Soft Scientific Research) Project (2025JH4/10100035) and Project of the Sichuan Provincial Key Laboratory of Philosophy and Social Sciences "Key Laboratory of Intelligent Emergency Management" (2025ZHYJGL-13).

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

The author(s) declared that generative AI was not used in the creation of this manuscript.

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