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Research Article

Analysis of Public Technology Collaborative Innovation Based on Private Technology: A Tripartite Evolutionary Game Approach

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Public technology collaborative innovation serves as an essential driving force to implement the innovation-driven strategy as well as promote national and regional economic sustainable development. Moreover, strengthening the construction of public technology collaborative innovation system is likewise of great significance for strengthening the quality and technology level of enterprises, enhancing their independent innovation capability, and achieving strategic transformation. Particularly, collaborative innovation of public technology in accordance with mature private technology enables the efficient allocation of technological and economic resources. In practice, there are still issues including high innovation costs, insufficient motivation, and low efficiency of innovation. Existing research typically ignores the technical cooperation among multiple parties. An evolutionary game model of public technology collaborative innovation is established in this paper to examine the interaction mechanism among the government, enterprises, and technology owners. For the purpose of analyzing the dynamic evolution of public technology collaborative innovation behavior and its influencing factors, numerical simulation experiments were conducted with meaningful results: (1) Setting the cost and benefit allocation coefficient in a scientific manner contributes to system stability and promotes cooperation among game players. (2) Reasonable government subsidies and penalties can assist in the formation of an active technological innovation between the firm and the technology owner. (3) The pricing method of private technology transfer is a significant factor influencing the evolution process. Besides, the adoption of a technology pricing method on the basis of government interests is conducive to the formation of a stable tripartite win-win situation. The research on collaborative innovation of public technology is further expanded in this paper, offering a reference for the formulation of relevant policies aimed at promoting cooperation in public technology innovation.

1. Introduction

Currently, countries worldwide should strive to continuously improve and enhance the provision of public goods in response to the evolving social needs of the public, including national defense and security, socially sustainable development, energy, and the environment. Hence, it is necessary to continue implementing technological advancements in public goods. Nowadays, innovation in the public sector is considered an open process of collaboration between stakeholders across various organizations [1]. Furthermore, collaboration is a more positive strategy for innovation in the public sector in comparison with strategies that seek isolation or competition [2]. Particularly collaborative innovation among participants from distinct sectors (governments, companies, nonprofit organizations, and universities, as well as other social groups) is increasingly promoted to stimulate more innovative activities [3]. Integrated innovation founded on big data technology is the foundation for effective outbreak prevention and control [4]. For instance, cross-industry collaborative innovation has played a positive position in the global fight against COVID-19 [5]. Scientific and technological strength, innovation, and industry-university-research cooperation play a function in technology integration and substantive support [4, 6]. This type of collaborative innovation grounded on cross-sectoral collaboration is gaining significance in norms and practices, as it is recognized as a necessary means to address the most pressing problems and challenges facing the public sector today [4, 7]. In addition, such cross-departmental cooperation is frequently employed in research on group decision-making to resolve conflicts among distinct stakeholders and finally reach a collective consensus [8–11]. Consequently, to effectively promote innovation in cross-sectoral collaboration and promote cooperation, it is necessary to analyze the factors influencing collaborative innovation and to clarify the action path of collaborative innovation systems.

Public technology innovation relates to the process of generating new product ideas according to social needs and existing technologies and developing new public products to meet social public needs through applied research, technology development, and transformation as well as application and eventually yielding social and economic benefits [12]. Besides, the private sector generally focuses on commercial, market, and technological innovations with the primary objective of creating value through increased profits or market share [13], whereas the public sector tends to focus on public and social innovation to create public value. It is widely assumed that the introduction of market-based competition and private-sector technologies will help the public sector become more innovative, flexible, and efficient [14]. Collaboration can benefit all steps of the innovation process and allows for the sharing of costs, risks, and rewards [15]. Research on the American Government Awards indicates that public innovation programs increasingly rely on intra- and interorganizational collaboration [15]. The nonprofit Benefits Data Trust (BDT) developed *BenePhilly*, in partnership and the Pennsylvania Departments of Aging and Human Services. *BenePhilly* has aided over 125,000 Philadelphia residents secure over $1.6 billion in benefits as of January 2021. The focus of this paper is placed on the technological innovation of public goods grounded on private technology, aiming to better meet public needs. Consequently, the issue addressed in this paper is the establishment of a scientific system for public technology collaborative innovation, the promotion of the application of proprietary technology achievements in the public domain, and the analysis of the influencing factors and action paths of the collaborative innovation participants.

Collaborative innovation can be broadly defined as innovation enabled through multiactor collaboration [15]. Besides, the existing research on public collaborative innovation primarily focused on benefits distribution, cooperation mode, and policy recommendations, as well as internal mechanisms. Al-Omoush et al. [5] empirically investigated the role of social capital in fostering collaborative innovation during the COVID-19 crisis. Vivona et al. [3] investigated how to reduce the cooperation cost of cross-departmental collaborative innovation by analyzing transaction cost theory, game theory, and knowledge theory. On the basis of transaction cost theory and the appropriability of knowledge, Audretsch and Belitski [16] adopted a resource-based perspective to concentrate on the constraints of open collaborative innovation. Moreover, Hartley et al. [14] drew on institutional and organizational theories in public administration and governance to answer the increasingly significant question of how to comprehend, analyze, and enhance public innovation collaboration. Furthermore, Wang et al. [17] adopted a holistic and longitudinal perspective to explore collaborative innovation networks. Schiuma and Santarsiero [18] used a systematic literature review to map the state of technology, providing insights and the necessary conceptual foundations for the design and management of innovation organizations. Taivalsaari Røhnebæk [19] employed methodology and empirical research to prove the relevance of the institutional logic perspective in collaborative innovation research. Except for that, Hwang [20] investigated the evolutionary mechanisms of the interfirm collaborative innovation network in the Korean ICT industry, the findings recommended that the government can encourage SMEs to participate in collaborative innovation by focusing on technological capability development. From the perspective of innovation diffusion theory, Zhou et al. [21] examined the mechanism of innovation behavior in CDW recycling public-private partnership projects. Also, the preceding literature provides a sufficient theoretical foundation for this paper's research.

Nonetheless, public technology collaborative innovation involves various factors, including actors as well as macroeconomic management of national economies, which should be seriously evaluated by all parties involved in the technological cooperation process. In traditional game theory, individuals are properly rational, and yet the players of the game are not completely rational in practice [22]. The evolutionary game theory takes the bounded rational game as the analytical framework and presumes that individuals can achieve dynamic equilibrium through study, imitation, and variation, thus compensating for some defects in traditional game theory, including perfect market competition and the economic theory hypothesis of rational economists [23]. On the condition that the balance achieved by game participants is not in line with the maximization of collective interests, the evolutionary game model can introduce government incentives and penalties, as well as other measures to ensure that the strategic choices of game participants achieve an ideal balance [24]. As research has progressed, the evolutionary game theory has been applied in a variety of fields. Babu and Mohan [25] applied evolutionary game theory to simulate stakeholders and revenue functions from multiple dimensions to evaluate the sustainability of the overall supply chain. Furthermore, Cai and Kock [26] examined the strategic interaction between two players in an electronic cooperation game by evolutionary game theory, filling the gap in the study of electronic cooperation within the context of game theory. In their study, Ji et al. [27] formulated an evolutionary game model to examine the cooperative tendencies among various stakeholders. Building upon this research, Chen et al. [28] extended the evolutionary game approach to investigate the factors contributing to the establishment of interpersonal cooperation mechanisms in the context of waste source separation.

Since it is frequently difficult to systematically analyze the interrelations between social sectors with multiple interests and potential differences, evolutionary game theory has been extensively applied to multiparty game issues, particularly when governments are involved. Encarnação et al. [29, 30] developed a new framework in accordance with evolutionary game theory to find that the public sector plays a major role in promoting the cooperation of various sectors. Moreover, Gu and Hang [31] constructed a behavioral interaction framework between innovative firms and local government regulators on the basis of evolutionary game analysis. Furthermore, Ji et al. [32] applied the indirect evolutionary game theory for the purpose of studying the interaction mechanism of complex behaviors between local governments and automobile manufacturers.

Besides, the research on innovative cooperation in accordance with evolutionary game theory has attracted the interest of academics. The application of the evolutionary game model to industry-university-research innovative cooperation is prevalent in recent years. Yang et al. [33] evaluated the government's industry-university-research intellectual property cooperation behavior as well as its influencing factors using evolutionary game theory. Moreover, Zan et al. [34] predominantly considered the effects of agent coupling degree, population size, and government policies on the steady evolution of industry-university-research collaborative innovation. In addition, Qu and Guo [35] investigated the influence of distinct technological characteristics on private enterprise and military enterprise, as well as the government under the condition of three-party evolutionary game models. The evolutionary game model is also utilized to analyze green technology innovation systems [36–39]. Yang et al. [40] adopted the game-based theory to indicate changes in game strategies in the course of green technology development. Derived from the coevolution theory, Li et al. [41] constructed a theoretical model of green innovation behavior at the environmental and organizational levels. Besides, Hao et al. [42] employed a tripartite evolutionary game model to unpack the black box of evolution mechanism in the recycling resources industry innovation ecosystem. Nonetheless, the research on technological cooperation innovation of heterogeneous agents is still relatively limited. Conflicts of interest among stakeholders will impede the realization of technological collaborative innovation [43]. Public technology collaborative innovation typically involves multiple stakeholders and many conflicts of interest, which would cause enormous obstacles to its accomplishment. The studies conducted have presented the fundamental model framework and analysis approach for the tripartite evolutionary game, serving as the basis for our research.

Currently, few studies examine technology transfer in the context of collaborative innovation, and the majority of these studies begin at the theoretical level. In practice, technology transfer plays an essential role in promoting the knowledge flow of collaborative innovators and the evolution of industry-university-research collaborative innovation. Moreover, it frequently takes crucial resources for a new technology or product to become viable, nonetheless, compared to the average cost of research, development, and application, the marginal cost of continuous application of the existing technology is negligible due to the low cost of transferring the existing innovation [44].

According to the literature retrieved, the existing research has a certain reference role for the development of collaborative innovation of public technology, and yet there are still the following problems. Besides, existing related studies generally dismissed the technological cooperation between multiple heterogeneous entities and are restricted to the technological cooperation innovation between firms. In most studies, government behavior is typically incorporated into the game model solely as exogenous variables, lacking a comprehensive game analysis involving the government as an active participant alongside firms and technology owners. In practice, various public products are put into use after innovative transformation derived from existing private technologies, which can shorten the R&D cycle as well as reduce the cost. Nonetheless, the majority of research fails to take into account the fact that the existing technological foundation can be employed for transformation and innovation.

In accordance with the abovementioned theory, the aim of this paper is to explore the technology collaborative innovation behavior of the government, firm, and technology owner using the evolutionary game method. In particular, on the basis of the situation that the game players can directly use the existing private technology to carry out technological transformation and innovation, through numerical analysis of the factors influencing collaborative innovation in public technology and focus on the analysis of the impact of technology transfer pricing method on the evolution strategy.

Besides, the innovation of this paper is as follows. In theory, the evolution process of public technology collaborative innovation behavior is revealed by this study. In practice, the research on public technology collaborative innovation mechanisms derived from existing private technology is expanded by this study. Furthermore, this study analyzes the effect of technology transfer pricing on the evolution process and contains policy recommendations for the government to encourage collaborative innovation of public technology.

The rest of this paper is organized as follows. Section 2 predominantly carries out the basic assumption and construction of the model. Section 3 serves as an evolutionary stability strategy analysis derived from the replication dynamic equation. Section 4 includes the numerical simulation and analysis of the influence of the corresponding parameters on the evolutionary game. Section 5 expands the model and analyzes the effect of the pricing method for technology transfer on the evolution strategy. Finally, Section 6 summarizes the primary findings as well as recommendations.

2. Problem Description and Model Assumptions

Derived from the previous studies [35, 40, 45–47], a three-party evolutionary game model is constructed for the collaborative innovation of public technology, employing a general solution method. The distinguishing feature of our paper, compared to previous studies, is the inclusion of the technology transfer process in two distinct cases between the firm and the technology owner, which is explicitly incorporated into the model.

The game players in the model are *the government* (G), *firm* (F), and *technology owner* (T).

2.1. The Government. The government, as the purchaser of public technology, organizes collaborative public technology innovation. It can participate in the collaborative innovation system of public technology utilizing financial subsidies or punishment regulation [48]. Initially, the government utilizes its dominant market position to select the technology owner with a particular technological foundation.

2.2. The Technology Owner. The technology owner is the key body supporting collaborative innovation, which primarily relates to the scientific research institution or university that has mastered the core private technology necessary for collaborative innovation.

2.3. The Firm. The firm primarily provides innovation resources and promotes the innovation and output of innovation achievements. In order to bridge the gap between private technology in the general commercial market and the public technology required by the government, further technological innovation is imperative to meet the demand of the public sector.

For the purpose of simplifying this issue, our paper assumes the following points.

Assumption 1. The players of the game behaviors in the model are all bounded rationality. Players choose strategies in accordance with their own needs and decide the behaviors of the next round in accordance with the comparison between the benefits generated by the behaviors of the current round and that of other game players.

Assumption 2. The government can choose to participate in the collaborative innovation system, or it may opt out of participation. The proportion of participation is x, subsequently, the proportion of nonparticipation is $1-x$. Besides, the proportion of the firm choosing to participate in collaborative innovation is y, and the proportion of nonparticipation is $1-y$. The proportion of the technology owner selecting to engage in collaborative innovation is z, and the proportion of nonparticipate is $1-z$. Here, x, y, and z belong to $[0,1]$.

Assumption 3. The benefits obtained when the government chooses to participate in the collaborative innovation system are R_1. To encourage firm and technology owner participation in collaborative innovation, the government will implement regulatory and incentive measures. C_1 represents the cost of government participation. C denotes the total cost of collaborative innovation. The government's implementation of incentive measures will reduce C by S. Moreover, a represents the cost allocation coefficient. Consequently, the cost of the firm is $a(C-S)$, while the cost of the technology owner is $(1-a)(C-S)$. To ensure the successful completion of technological innovation, the government will provide subsidy support S_1 and S_2 for the firm and the technology owner participating in technological innovation, correspondingly. When the government does not participate in collaborative innovation, its revenue will become $R_2 = bR_1$, where b pertains to $[0,1]$. To encourage the firm and the owner of the technology to participate in technological innovation, the government employs punitive oversight over the firm and the owner of the technology. Either party should pay the other party the fee k for the abandonment of cooperation.

Assumption 4. The initial benefits of the firm and the technology owner are R_3 and R_4, respectively. On the condition that the firm and the technology owner jointly participate in the collaborative innovation, the overall additional revenue is R. Besides, c represents the revenue sharing coefficient, including the revenue of the firm is cR and the revenue of the technology owner is $(1-c)R$. If the owner of the technology prefers not to participate in the collaborative innovation, then the technology owner will transfer the technology to the firm at a fixed fee F_1. After acquiring the fundamental technology, the company can independently innovate and implement it in production. C_2 represents the innovation cost of the firm. r_3 represents the benefits obtained by the firm through independent technological innovation. In the same way, when the firm opts not to take part in the cooperation, the technology owner will conduct out the technological innovation independently. C_3 represents the innovation cost of the technology owner. Subsequently, the firm could obtain the completed technology for a fixed fee F_2 from the technology owner. r_4 symbolizes the profits of the firm through product production.

3. Stability Analysis of Evolutionary Strategies

The tripartite mixed strategy game matrix of the government, firm, and technology owner is established according to the above assumptions (Table 1).

3.1. Game Equilibrium Analysis of the Government. The expected benefits of the government preferring to play an active role in collaborative innovation are U_{11}.

$$\begin{aligned} U_{11} = {} & yz(R_1 - C_1 - S_1 - S_2) + (1-y)z(R_1 - C_1 - S_2) \\ & + y(1-z)(R_1 - C_1 - S_1) + (1-y)(1-z)(R_1 - C_1). \end{aligned} \tag{1}$$

The expected benefits of the government selecting not to engage in collaborative innovationare U_{12}.

$$U_{12} = yzR_2 + (1-y)zR_2 + y(1-z)R_2 + (1-y)(1-z)R_2. \tag{2}$$

The average expected benefits of the government are $\overline{U_1}$.

$$\overline{U_1} = xU_{11} + (1-x)U_{12}. \tag{3}$$

Table 1: Mixed strategy game matrix.

	Government participation (x)		No government participation $(1-x)$	
	Firm cooperation (y)	No firm cooperation $(1-y)$	Firm cooperation (y)	No firm cooperation $(1-y)$
Technology owner collaboration (z)	$R_1 - C_1 - S_1 - S_2$ $R_3 + cR - a(C - S)$ $R_4 + (1-c)R - (1-a)(C - S)$	$R_1 - C_1 - S_2$ $R_3 - F_2 + r_4 - k$ $R_4 + S_2 - C_3 + F_2 + k$	R_2 $R_3 + cR - aC$ $R_4 + (1-c)R - (1-a)C$	R_2 $R_3 - F_2 + r_4$ $R_4 - C_3 + F_2$
No technology owner collaboration $(1-z)$	$R_1 - C_1 - S_1$ $R_3 - F_1 - C_2 + r_3 + S_1 + k$ $R_4 + F_1 - k$	$R_1 - C_1$ R_3 R_4	R_2 $R_3 - F_1 - C_2 + r_3$ $R_4 + F_1$	R_2 R_3 R_4

The replication dynamic equation can be obtained from equations (1)–(3).

$$F(x) = \frac{\mathrm{d}x}{\mathrm{d}t} = x(U_{11} - \overline{U_1}) = x(1-x)[(1-b)R_1 - C_1 - yS_1 - zS_2]. \quad (4)$$

The first derivative of $F(x)$ is as follows:

$$\frac{\mathrm{d}F(x)}{\mathrm{d}x} = (1-2x)m(y) = (1-2x)[(1-b)R_1 - C_1 - yS_1 - zS_2]. \quad (5)$$

The conditions that need to be satisfied on the condition that the probability of the government choosing to participate is in a steady state are $F(x) = 0$ and $(\mathrm{d}F(x)/\mathrm{d}x) < 0$. If $F(x) = 0$ and $F^{'}(x) < 0$, x is the evolutionary stability strategy (ESS).

① If $m(y) = 0$, $y^* = ((1-b)R_1 - C_1 - zS_2/S_1)$ and $F(x) \equiv 0$. In this case, the government is in a stable state of evolutionary game, and consequently, its stable strategy cannot be determined.

② If $m(y) > 0$, $y < y^*$, and $(\mathrm{d}F(x)/\mathrm{d}x)|_{x=1} < 0$, $x = 1$ is the ESS. In this case, the government tends to prefer to participate in collaborative innovation.

③ If $m(y) < 0$, $y > y^*$, and $(\mathrm{d}F(x)/\mathrm{d}x)|_{x=0} < 0$, $x = 0$ is the ESS. In this case, the government is typically unwilling to engage in collaborative innovation.

The phase of the government's strategy evolution process is indicated in Figure 1.

3.2. Game Equilibrium Analysis of the Firm. The expected benefits of the firm deciding to engage in collaborative innovation are U_{21}:

$$\begin{aligned} U_{21} &= \mathrm{xz}(R_3 + cR - a(C - S)) + (1-x)z(R_3 + cR - aC) \\ &\quad + x(1-z)(R_3 - F_1 - C_2 + r_3 + S_1 + k) + (1-x)(1-z)(R_3 - F_1 - C_2 + r_3). \end{aligned} \quad (6)$$

The expected benefits of the firm preferring not to participate in collaborative innovation are U_{22}:

$$\begin{aligned} U_{22} &= \mathrm{xz}(R_3 - F_2 + r_4 - k) + (1-x)z(R_3 - F_2 + r_4) \\ &\quad + x(1-z)R_3 + (1-x)(1-z)R_3. \end{aligned} \quad (7)$$

The average expected benefits of the firm are $\overline{U_2}$:

$$\overline{U_2} = yU_{21} + (1-y)U_{22} \quad (8)$$

Besides, the replication dynamic equation can be obtained from equations (6)–(8).

$$F(y) = \frac{\mathrm{d}y}{\mathrm{d}t} = y(U_{21} - \overline{U_2}) = y(1-y)[z(cR + F_2 - aC - r_4) + (1-z)(r_3 - F_1 - C_2) + x(k + S_1 + z(aS - S_1))]. \quad (9)$$

The first derivative of $F(y)$ is as follows:

$$\frac{\mathrm{d}F(y)}{\mathrm{d}y} = (1-2y)n(x) = (1-2y)[z(cR + F_2 - aC - r_4) + (1-z)(r_3 - F_1 - C_2) + x(k + S_1 + z(aS - S_1))]. \quad (10)$$

The conditions that need to be satisfied on the condition that the probability of the firm preferring to participate is in a steady state are: $F(y) = 0$ and $(\mathrm{d}F(y)/\mathrm{d}y) < 0$. Since $(\partial n(x)/\partial x) > 0$, $n(x)$ is monotonically increasing. If $F(y) = 0$, $F^{'}(y) < 0$, y is the ESS.

① If $n(x) = 0$, $x^* = (F_1 + C_2 - r_3 + z(r_3 + aC + r_4 - F_1 - C_2 - cR - F_2)/k + S_1 + z(aS - S_1))$ and $F(y) \equiv 0$. In this case, the firm is in the stable state of evolutionary game, and consequently, its stable strategy cannot be determined.

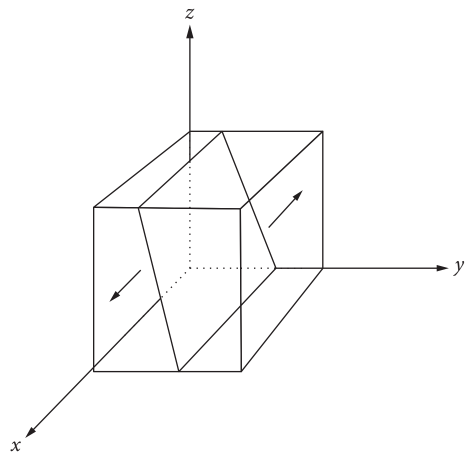


Figure 1: Phase diagram of the government's strategy evolution process.

② If $n(x) > 0$, $x > x^*$, and $(dF(y)/dy)|_{y=1} < 0$, $y = 1$ is the ESS. In this case, typically, the firm opts to engage in collaborative innovation.

③ If $n(x) < 0$, $x < x^*$, and $(dF(y)/dy)|_{y=0} < 0$, $y = 0$ is the ESS. In this case, the firm tends to choose not to participate in collaborative innovation.

The phase of the firm's strategy evolution process is illustrated in Figure 2.

3.3. Game Equilibrium Analysis of the Technology Owner. The expected benefits of the technology owner choosing to participate in collaborative innovation are U_{31}:

$$\begin{aligned} U_{31} &= xy\left(R_4 + (1-c)R - (1-a)(C-S)\right) + (1-y)x\left(R_4 + S_2 - C_3 + F_2 + k\right) \\ &\quad + y(1-x)\left(R_4 + (1-c)R - (1-a)C\right) + (1-x)(1-y)\left(R_4 - C_3 + F_2\right). \end{aligned} \tag{11}$$

Moreover, the expected benefits of the technology owner deciding not to participate in collaborative innovation are U_{32}:

$$U_{32} = xy\left(R_4 + F_1 - k\right) + (1-y)xR_4 + y(1-x)\left(R_4 + F_1\right) + (1-x)(1-y)R_4. \tag{12}$$

The average expected benefits of the technology owner are $\overline{U_3}$:

$$\overline{U_3} = zU_{31} + (1-z)U_{32}. \tag{13}$$

The replication dynamic equation can be obtained from equations (11)–(13).

$$F(z) = \frac{dz}{dt} = z\left(U_{31} - \overline{U_3}\right) = z(1-z)\left\{y\left[(1-c)R - (1-a)C - F_1\right] + xy(1-a)S + (1-y)\left(F_2 - C_3\right) + x(1-y)S_2 + xk\right\}. \tag{14}$$

The first derivative of $F(z)$ is as follows:

$$\frac{dF(z)}{dz} = (1-2z)p(x) = (1-2z)\left\{y\left[(1-c)R - (1-a)C - F_1\right] + xy(1-a)S + (1-y)\left(F_2 - C_3\right) + x(1-y)S_2 + xk\right\}. \tag{15}$$

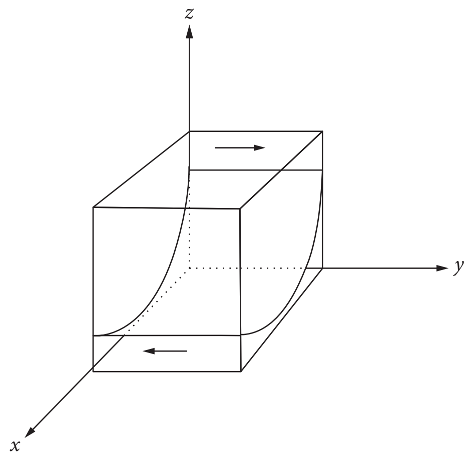


Figure 2: Phase diagram of the firm's strategy evolution process.

The conditions that need to be satisfied when the probability of the technology owner choosing to participate are in a steady state, namely, $F(z) = 0$ and $(\mathrm{d}F(z)/\mathrm{d}z) < 0$. Since $(\partial p(x)/\partial x) > 0$, $p(x)$ is monotonically increasing. If $F(z) = 0$, $F'(z) < 0$. z is the ESS.

① If $p(x) = 0$, $x^{**} = (C_3 - F_2 - y[(1-c)R - (1-a)C - F_1 + C_3 - F_2]/k + S_2 + y[(1-a)S - S_2])$ and $F(z) \equiv 0$. In this case, the technology owner is in the stable state of the evolutionary game, and consequently, its stable strategy cannot be determined.

② If $p(x) > 0$, $x > x^{**}$, and $(\mathrm{d}F(z)/\mathrm{d}z)|_{z=1} < 0$. $z = 1$ is the ESS. In this case, the technology owner tends to decide to participate in collaborative innovation.

③ If $p(x) < 0$, $x < x^{**}$, and $(\mathrm{d}F(z)/\mathrm{d}z)|_{z=0} < 0$. $z = 0$ is the ESS. In this case, the technology owner prefer not to participate in collaborative innovation.

The phase of the technology owner's strategy evolution process is illustrated in Figure 3.

3.4. Stability Analysis of Equilibrium Point in Tripartite Evolutionary Game. The preceding discussion is conducted from the perspective of the government, firm, and technology owner and the strategy of the three-game players are comprehensively analyzed. Equations (4), (9), and (14) are combined to acquire the duplicate dynamic system equations of the evolutionary game among the government, firm, as well as technology owner.

$$\begin{cases} F(x) = x(1-x)[(1-b)R_1 - C_1 - yS_1 - zS_2], \\ F(y) = y(1-y)[z(cR + F_2 - aC - r_4) + (1-z)(r_3 - F_1 - C_2) + x(k + S_1 + z(aS - S_1))], \\ F(z) = z(1-z)\{y[(1-c)R - (1-a)C - F_1] + xy(1-a)S + (1-y)(F_2 - C_3) + x(1-y)S_2 + xk\}. \end{cases} \tag{16}$$

By solving the aforementioned equations of duplicated dynamical systems, the pure strategy equilibrium solutions can be obtained, including $E_1(0,0,0)$, $E_2(1,0,0)$, $E_3(0,1,0)$, $E_4(0,0,1)$, $E_5(1,1,0)$, $E_6(1,0,1)$, $E_7(0,1,1)$, $E_8(1,1,1)$, and the mixed strategy equilibrium solution. In the asymmetric game model, if the condition of information asymmetry holds, the evolutionarily stable strategy must be a straightforward strategy [49, 50]. If the equilibrium of the evolutionary game is asymptotically stable, it must be a strict Nash equilibrium. Besides, strict Nash equilibrium is a pure strategy, that is, the mixed strategy equilibrium of the asymmetric game cannot be evolutionarily stable. Thus, only the asymptotic stability of eight pure strategy equilibrium points $E_1 \sim E_8$ in the dynamic replication system needs to be discussed in this model.

In accordance with the existing literature research basis [51–53], it is obvious that Lyapunov's rule is effective in verifying system stability and equilibrium point analysis. Lyapunov stability, as a general method for analyzing the stability of univariable, multivariable, linear, nonlinear, and time-varying systems, is built upon the state-space description method of the system, which not only describes the external characteristics of the system but also fully reveals its internal characteristics. According to Lyapunov's first law, we solved the differential equations of the system and subsequently judge the stability of the system built upon the properties of the solutions.

The eigenvalues of the Jacobian matrix of the dynamic replication system of the tripartite evolutionary game at the equilibrium point are λ_1, λ_2, and λ_3 in accordance with Lyapunov's first law. If $\lambda_1 < 0$, $\lambda_2 < 0$, and $\lambda_3 < 0$, the equilibrium point is asymptotically stable. If $\lambda_1 > 0$, $\lambda_2 > 0$, and $\lambda_3 > 0$, the equilibrium point is unstable. The equilibrium point is unstable if there is at least one plus and one minus between λ_1, λ_2, and λ_3.

The following represents the Jacobian matrix of the system:

$$J = \begin{bmatrix} (1-2x)[(1-b)R_1 - C_1 - yS_1 - zS_2] & -x(1-x)S_1(1-2y) & -x(1-x)S_2 y(1-y) \\ y(1-y)[(k+S_1) + z(aS - S_1)] & [z(cR + F_2 - aC - r_4) + (1-z)(r_3 - F_1 - C_2) + x(k + S_1) + xz(aS - S_1)] & [cR + F_2 - aC - r_4 - r_3 + F_1 + C_2 + x(aS - S_1)] \\ z(1-z)[y(1-a)S + (1-y)S_2 + k] & z(1-z)[(1-c)R - (1-a)C - F_1 + x(1-a)S - (F_2 - C_3) - xS_2] & (1-2z)\{y[(1-c)R - (1-a)C - F_1] + xy(1-a)S + (1-y)(F_2 - C_3) + x(1-y)S_2 + xk\} \end{bmatrix}. \tag{17}$$

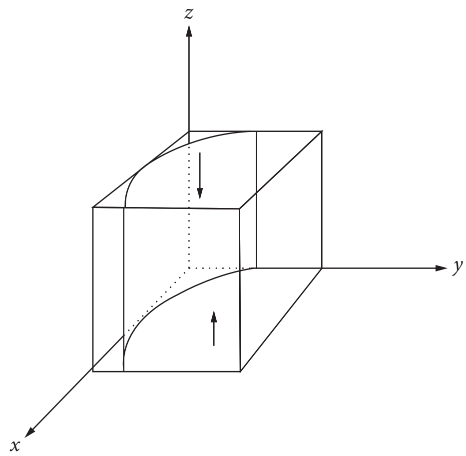


Figure 3: Phase diagram of the technology owner's strategy evolution process.

The Jacobian matrix eigenvalues of each equilibrium point are demonstrated in Table 2.

Conditions ①–⑨ are assumed to facilitate the analysis of eigenvalue symbols at distinct equilibrium points.

① $F_2 > C_3$. The price of the technology upon the completion of the innovation is greater than the cost of technological innovation, which is the rational constraint condition for the technology owner to carry out technology innovation independently.

② $r_3 - F_1 - C_2 > 0$. The benefits acquired by the firm from participating in technological innovation are greater than the cost of technological innovation, which is the rational constraint condition for the firm to conduct technological innovation independently.

③ $r_4 - F_2 > 0$. The benefits obtained by the firm from product production are greater than the cost of purchasing the technology, which is the rational constraint condition for the firm.

④ $(1-b)R_1 - C_1 - S_1 - S_2 > 0$. The advantages of government participation in collaborative technological innovation outweigh those of nonparticipation.

⑤ $r_4 + a(C-S) - cR - F_2 - k < 0$. Under the condition of government participation, the benefits of the firm participating in collaborative innovation are larger than that of nonparticipation.

⑥ $(1-c)R - F_1 - (1-a)(C-S) + k > 0$. Under the condition of government participation, the benefits of the technology owner participating in collaborative innovation are greater than that of nonparticipation.

⑦ $(1-b)R_1 - C_1 < 0$. Government participation in collaborative innovation provides fewer benefits than nonparticipation.

⑧ $(1-c)R - F_1 - (1-a)(C-S) + k < 0$. Under the condition of government participation, the benefits of the technology owner participating in collaborative innovation are less than that of nonparticipation.

⑨ $r_4 + a(C-S) - cR - F_2 - k > 0$. Under the condition of government participation, the benefits of the firm participating in collaborative innovation are less than that of nonparticipation.

For the purpose of simplifying the model parameters and facilitating the assessment of equilibrium point stability, an analysis of pivotal scenarios is conducted. Also, stability analysis of each equilibrium point is demonstrated in Table 3.

Case 1: if $F_2 > C_3$, $r_3 - F_1 - C_2 > 0$, $(1-b)R_1 - C_1 - S_1 - S_2 > 0$, $r_4 + a(C-S) - cR - F_2 - k < 0$ and $(1-c)R - F_1 - (1-a)(C-S) + k > 0$, the replication dynamic systems have a stable point $E_8(1,1,1)$.

Proof of Case 1: the stability of each equilibrium point is judged according to the eigenvalues of the Jacobian matrix in Table 2. If the conditions of Situation 1 are met, despite the fact that the technology owner and firm will not incur a loss if they participate in the technological innovation alone, all three parties stand to benefit more from participation. In this case, the stable strategy combination is (*participation, participation, and participation*).

Case 2: if$r_3 - F_1 - C_2 > 0, (1-c)R - F_1 - (1-a)(C-S) + k > 0, (1-b)R_1 - C_1 - S_1 - S_2 > 0$, $r_4 + a(C-S) - cR - F_2 - k > 0$ and $F_2 > C_3$, the replication dynamic systems have a stable point $E_6(1,0,1)$.

Proof of Case 2: if the conditions in Situation 2 are satisfied, the government and the technology owner can acquire higher benefits by participating in collaborative innovation. Nonetheless, the benefits obtained by the firm in participation are less nonparticipation. In this case, the stable strategy combination is (participation, nonparticipation, and participation).

Case 3: if $r_3 - F_1 - C_2 > 0$, $r_4 + a(C-S) - cR - F_2 - k > 0$, $(1-c)R - F_1 - (1-a)(C-S) + k < 0$ and $F_2 > C_3$. The replication dynamic systems have two stable points: $E_5(1,1,0)$ and $E_6(1,0,1)$.

Proof of case 3: in case 3, neither the firm nor the technology owner can obtain higher benefits by participating in collaborative innovation. At this time, it is preferable to independently pursue technological innovation. The stable strategy combination is (participation, nonparticipation, and participation) and (participation, participation, and nonparticipation).

4. Numerical Simulation

For the purpose of further studying the evolutionary game mechanism of the system and verifying the rationality of the above stability analysis, this study takes advantages of MATLAB R2022a software for simulation and evaluates the evolutionary process of the system according to the simulation results. Rooted in the actual situation and the basic assumptions of the model, the simulation parameters satisfy the conditions in Situation 1: $R = 400$, $R_1 = 300$, $r_3 = 50$, $r_4 = 50$, $S = 50$, $S_1 = 20$, $a = b = c = 0.5$, $S_2 = 30$, $C = 100$,

Table 2: Eigenvalues of Jacobi matrix.

Equilibrium points	Jacobian matrix eigenvalues $\lambda_1, \lambda_2, \lambda_3$
$E_1(0,0,0)$	$F_2 - C_3$, $r_3 - F_1 - C_2$, $(1-b)R_1 - C_1$
$E_2(1,0,0)$	$C_1 - (1-b)R_1$, $F_2 - C_3 + S_2 + k$, $S_1 - F_1 - C_2 + k + r_3$
$E_3(0,1,0)$	$C_2 + F_1 - r_3$, $(1-b)R_1 - C_1 - S_1$, $(1-c)R - F_1 - (1-a)C$
$E_4(0,0,1)$	$C_3 - F_2$, $(1-b)R_1 - C_1 - S_2$, $F_2 - r_4 - aC + cR$
$E_5(1,1,0)$	$C_1 - (1-b)R_1 + S_1$, $C_2 + F_1 - S_1 - k - r_3$, $(1-c)R - F_1 - (1-a)(C-S) + k$
$E_6(1,0,1)$	$C_1 - (1-b)R_1 + S_2$, $C_3 - F_2 - S_2 - k$, $F_2 + k - r_4 - a(C-S) + cR$
$E_7(0,1,1)$	$r_4 + aC - cR - F_2$, $(1-a)C + F_1 - (1-c)R$, $(1-b)R_1 - C_1 - S_1 - S_2$
$E_8(1,1,1)$	$C_1 - (1-b)R_1 + S_2 + S_1$, $r_4 + a(C-S) - cR - F_2 - k$, $(1-a)(C-S) - (1-c)R + F_1 - k$

$C_1 = 50$, $C_2 = 20$, $C_3 = 18$, $k = 5$, $F_1 = 10$, and $F_2 = 20$. Suppose that the initial willingness of game players to participate is $x = y = z = 0.5$. The effects of benefits, penalties, benefit-sharing coefficient, government subsidies, initial willingness to participate, and technology transfer pricing mode on the evolutionary game were discussed based on the simulation results.

4.1. Analysis of the Influence of Benefits on Evolutionary Game. Observing the Jacobian matrix eigenvalues of the replicator dynamic equation system, it can be found that the evolutionary game process is not affected by the initial benefits of the firm and the technology owner. Due to the fact that the initial benefits of the firm and the technology owner are inherent properties, it has nothing to do with whether they participate in collaborative innovation. Thus, only the effects of R, R_1, r_3, and r_4 need to be considered. The influence of this factor is generally ignored in existing studies [34, 46, 54].

First, the influence of R on the evolutionary game was analyzed. The number of evolutions over time was set to 50. The numerical simulation analysis was performed on the replicated dynamic equations. Besides, the evolution results were revealed in Figure 4(a). The improvement of R can increase the probability of the firm and technology owner participating in collaborative innovation. Moreover, the stability strategy converges to the equilibrium point E_8, whereas the convergence speed gradually slows down as it approaches the equilibrium point. When R are relatively low ($R = 50$), condition ⑤ cannot be satisfied. In this case, the firm that participates in collaborative innovation receives fewer benefits than if it had not participated. Shifting to Situation 2, the evolution strategy of the firm will be adjusted to nonparticipation. The firm is more sensitive to the changes of benefits in collaborative innovation than the technology owner. Hence, the improvement of R will help to improve the degree of participation of the firm and technology owner, particularly the firm.

In the same way, we changed the parameters and carried out a numerical simulation of R_1, r_3, and r_4, subsequently carried out the simulation of evolution with time. As revealed in Figure 4(b), when R_1 are relatively low, condition ⑦ is satisfied. In this case, the government will decline to engage in collaborative innovation. With the increase of R_1, the willingness for government participation keeps rising. When x evolves from 0 to 1, it implies that the government will ultimately prefer to participate in collaborative innovation. As the increase of R_1, the probability of government participation will steadily decrease. This is due to the fact that when the government chooses not to participate, its benefits $R_2 = bR_1$ likewise increase. Hence, the government will evaluate the net benefit in the two cases to adjust its game strategy.

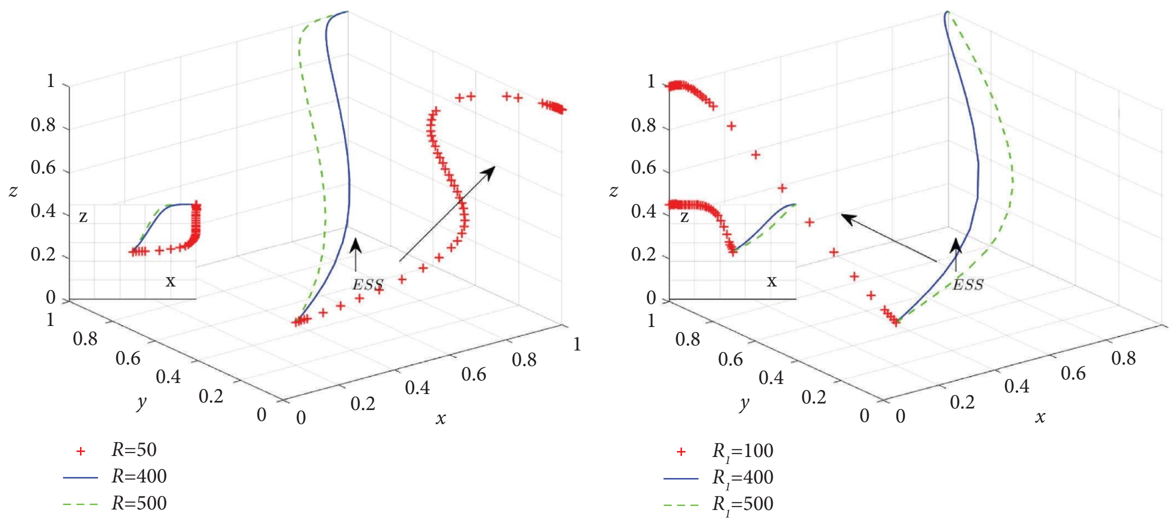
As displayed in Figure 5(a), the firm can pay less R&D cost of technological innovation through collaborative innovation. By utilizing government support policies, the company can obtain new technologies through collaboration and generate profits. Consequently, under the benefits orientation, higher innovation benefits will improve the enthusiasm of the firm to participate in collaborative innovation, the stable evolution strategy combination of the system is (participation, nonparticipation, and participation).

The improvement of r_4 will decrease the likelihood of firm participation in collaborative innovation. When r_4 increases to a certain extent and meets the condition ⑨, the firm can obtain higher benefits even if the company does not engage in collaborative innovation. In this case, the system's stability may be destroyed. Moreover, the firm will choose not to participate in collaborative innovation and ultimately converge to the equilibrium point E_6 (Figure 5(b)).

4.2. Analysis of the Influence of Punishment Regulation on Evolutionary Game. In this section, the punishment factors are adjusted and the influence of the degree of punishment on the evolutionary game is analyzed (Figure 6). When the punishment intensity is relatively low ($k = 5$), the probability of the technology owner preferring not to participate in collaborative innovation is relatively large. In addition, the firm's willingness to participate will decrease. In this case, the conditions in Situation 2 are satisfied. With the increase in punishment intensity, the benefits of the technology owner and the firm will alter. Also, the benefits of not participating in collaborative innovation will be substantially reduced. The technology owner may tend to participate in collaborative innovation in order to obtain higher profits, which will contribute to the firm paying a higher price and finally choosing to participate in collaborative innovation. It can be found that the convergence speed of the firm is dramatically higher than that of the technology owner. The firm is more sensitive to the intensity of punishment that is due to the fact that it focuses more on the maximization of economic returns. Changes in the intensity of punishment will lead to a rapid change in its willingness of participate. Consequently, the government's strengthening of punishment supervision will be more accommodating to promoting the firm to participate in the collaborative innovation of public technology, which is consistent with those studies [33, 55].

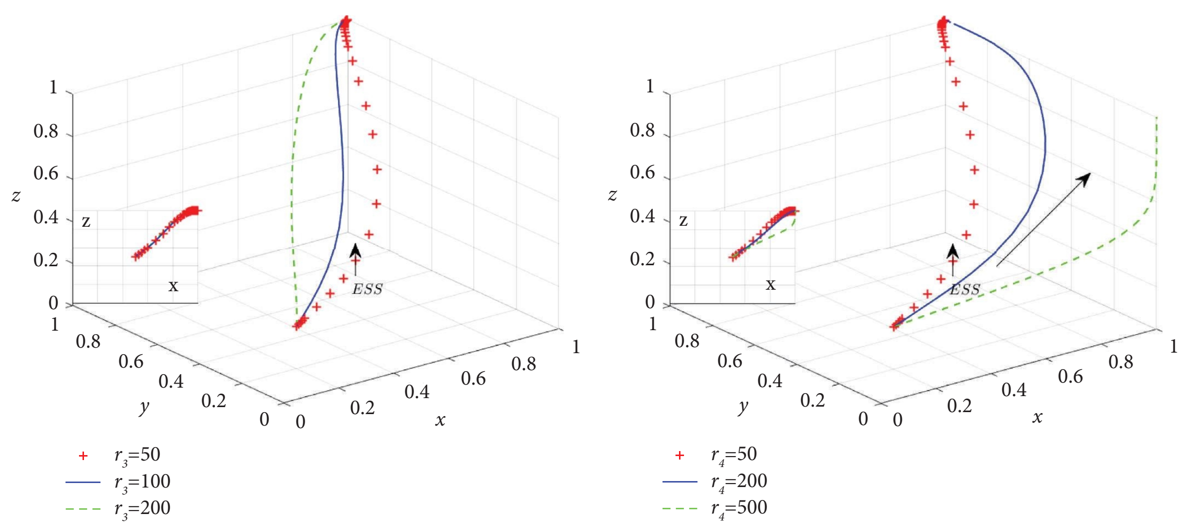
Table 3: Stability analysis of equilibrium points.

Equilibrium points	Situation 1			Situation 2			Situation 3		
	Condition	Symbol	State	Condition	Symbol	State	Condition	Symbol	State
$E_1\,(0,0,0)$	①②④	$(+,+,+)$	Instability point	①②④	$(+,+,+)$	Instability point	①②④	$(+,+,+)$	Instability point
$E_2\,(1,0,0)$	①④	$(-,+,\times)$	Saddle point	①④	$(-,+,\times)$	Instability point	①④	$(-,+,\times)$	Saddle point
$E_3\,(0,1,0)$	②④	$(-,+,\times)$	Saddle point	②④	$(-,+,\times)$	Saddle point	②④	$(-,+,\times)$	Saddle point
$E_4\,(0,0,1)$	①④	$(-,+,\times)$	Saddle point	①④	$(-,+,\times)$	Saddle point	①④	$(-,+,\times)$	Saddle point
$E_5\,(1,1,0)$	②④⑥	$(-,-,+)$	Instability point	②④⑥	$(-,-,+)$	Instability point	②④⑧	$(-,-,-)$	ESS
$E_6\,(1,0,1)$	①④⑤	$(-,-,+)$	Instability point	①④⑨	$(-,-,-)$	ESS	①④⑨	$(-,-,-)$	ESS
$E_7\,(0,1,1)$	④	$(\times,\times,+)$	Saddle point	④	$(\times,\times,+)$	Saddle point	④	$(\times,\times,+)$	Saddle point
$E_8\,(1,1,1)$	④⑤⑥	$(-,-,-)$	ESS	④⑨	$(-,+,+)$	Instability point	④⑧⑨	$(-,+,+)$	Instability point



(a) (b)

FIGURE 4: (a) The effect of R on the strategy evolution. (b) The effect of R_1 on the strategy evolution.



(a) (b)

FIGURE 5: (a) The effect of r_3 on the strategy evolution. (b) The effect of r_4 on the strategy evolution.

4.3. Analysis of the Influence of Apportionment Coefficients on the Evolutionary Game. Cost and benefit are the key factors in collaborative innovation decision-making, particularly setting a reasonable cost and benefit-sharing plan that can effectively reduce opportunistic behavior in cooperation [56]. Due to the significance of the cost and benefit allocation coefficient, the impact of collaborative innovation is analyzed in this section.

First, the influence of the cost allocation coefficient of collaborative innovation on the evolutionary game is examined. As displayed in Figure 7(a), the simulation analysis of evolution over time was conducted. If the cost allocation coefficient is low ($a = 0.1$), the conditions in Situation 3 are satisfied. In this case, the firm needs to pay less cost than the technology owner. Moreover, the firm has a stronger willingness to participate, while the technology owner needs to present its private technology, as well as need to bear most of the cost of technology innovation. Thus, the willingness of the technology owner to participate will decrease continuously and the convergence rate is accelerating. The equilibrium point ultimately tends to E_5. With the constant rise of the cost allocation coefficient ($a = 0.9$), the cost apportionment of the technology owner will continue to decrease. Thus, the participation willingness of the technology owner will gradually increase. Concurrently, the firm's participation willingness will decrease gradually. Also, the final equilibrium point tends to E_6. If $a = 0.3$, both the firm and the technology owner will prefer to participate in collaborative innovation. y and z will converge to 1 and the convergence speed will accelerate. The equilibrium point

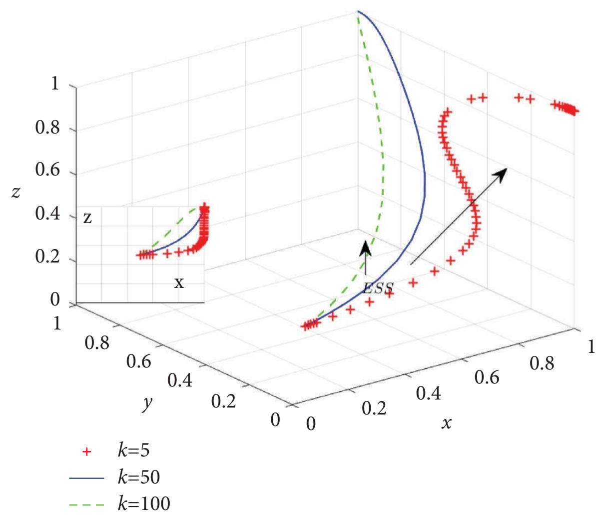


FIGURE 6: The effect of k on the strategy evolution.

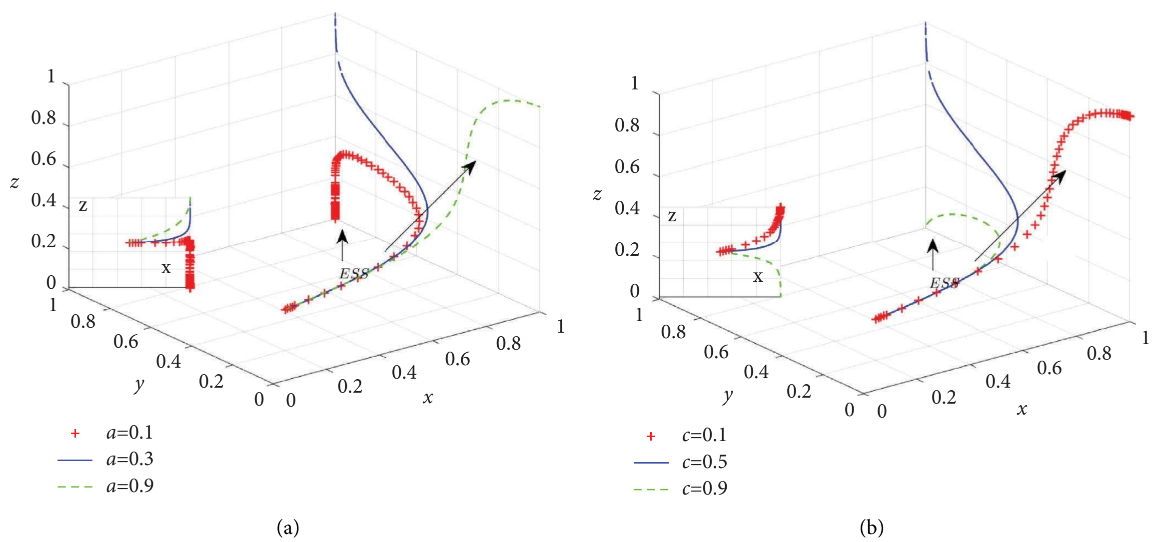


FIGURE 7: (a) The effect of a on the strategy evolution. (b) The effect of c on the strategy evolution.

eventually tends to E_8. This suggests that the cost allocation rate will influence the system's stability. The party that bears more costs will get fewer benefits, which will contribute to a reduction of its willingness to participate.

Secondly, the influence of the benefit allocation coefficient on the evolutionary game is explored. As indicated in Figure 7(b), the change of c is exactly the opposite of a. When $c = 0.1$, the benefits of the firm are not guaranteed. As a direct consequence, their willingness to participate gradually declines, contributing to an eventual equilibrium point E_6. This implies that the firm will not prefer to participate in collaborative innovation. When $c = 0.9$, the technology owner may get less apportioned benefits. Therefore, the owner of the technology will not choose to engage in collaborative innovation. Finally, the equilibrium point tends to E_5. When $c = 0.5$, the convergence rate of both parties is consistent and the evolution process is stable. In this case, the equilibrium point tends to E_8 in the end.

Both the firm's and the technology owner's evolutionary strategies are sensitive to the change in cost and benefit allocation coefficient. These conclusions are in agreement with Yang et al. [40] who presumed that in the absence of an efficient distribution mechanism, the performance of collaborative innovation was inadequate. If the allocation coefficients are set improperly, one party will choose not to participate in collaborative innovation. As a consequence, the scientific setting of the cost and benefit allocation coefficient is conducive to preserving the system's stability and the synergy of game players.

4.4. Analysis of the Influence of Government Subsidies on Evolutionary Game. It is observed that public innovation subsidies within a reasonable range can achieve the same incentive effect. In a broad sense, the government wants to promote cooperation with minimal subsidies under financial pressure. Besides, the existing research indicates that the probability of noncooperation within the valid value range of public innovation subsidies will converge to zero [57]. Public funding subsidies can reduce the cost of a company's participation in collaborative innovation [58]. The government generally encourages the firm and the technology owner to participate in collaborative innovation through subsidies, which can be primarily divided into two types. The first type is collaborative innovation subsidies, which aim to lower the cost of collaborative innovation for both the firm and the technology owner, thereby increasing their incentives and benefits in the collaborative innovation process. The second type involves providing subsidies to parties involved in technological innovation to ensure the successful completion of the innovation activities. These subsidies are intended to facilitate and encourage the smooth progress of technological innovation endeavors.

First, the simulation analysis is conducted on the impact of S on the evolutionary game. Also, the evolutionary results are indicated in Figure 8(a). If the intensity of government subsidies is low, the firm with the goal of maximizing benefits will invariably decide not to engage in collaborative innovation. With the increase in subsidy intensity, the participation probability of the firm and the technology owner keeps increasing. During the same time, the convergence rate keeps accelerating. The equilibrium point eventually tends to E_8.

Consequently, when the firm participates in technological innovation alone, the government's punishment regulation decreases the firm's loss of independent technological innovation (Figure 8(b)). Even with low-intensity subsidies, the firm's willingness to participate can be enhanced. Ultimately, the evolution tends to the equilibrium point E_8. Currently, there is a need for attention to the magnitude of government subsidies. Excessive subsidies will undermine the interests of the government and cause the circumstance that the technology owner cannot profit from providing the private technology. Besides, the stability of the collaborative innovation system is damaged and eventually tends to E_3 (Situation 2).

Ultimately, if the technology owner participates in technological innovation alone, government subsidies will increase its participation probability (Figure 8(c)). By acquiring technology, the firm can profit from the production of public goods. Even if it does not participate in technological innovation, the willingness of the firm to participate in collaborative innovation will not be significantly affected by the technology owner's innovation subsidies. The final evolution tends to the equilibrium point E_8.

The simulation results indicate that government subsidies would affect the strategy selection of the evolutionary game. Since the firm has two functions of collaborative innovation and product production, its willingness to participate in collaborative innovation will not be greatly affected on the condition that the external environment changes. Also consequently, the owner of the technology is more responsive to government subsidy incentives. Thus, government subsidy policies need to be formulated in accordance with the characteristics of the firm and the technology owner to address the requirements of multiparty game players as far as possible. There are some researches [40, 59] that also report the above findings. Reasonable subsidy incentive measures can encourage more technology owners to invest in collaborative innovation and contribute their technologies as well as encourage firms to achieve the win-win goal of technological innovation and mass production.

4.5. Analysis of the Influence of Initial Participation Willingness on Evolutionary Game. To investigate the impact of varying initial participation willingness among game players on the stability of evolutionary strategies, we modify the initial willingness of participation while keeping all other parameters constant. Besides, the simulation analysis is carried out. Assuming the initial willingness of the three parties to participate is $x = y = z$, the initial values are set to 0.2, 0.5, and 0.7, correspondingly. Moreover, evolutionary simulation results are indicated in Figure 9.

Regardless of the initial willingness to participate, x, y, z will converge to 1 eventually. As initial willingness increases, the rate of convergence accelerates. With the same initial willingness to participate, the convergence speed of the firm and the technology owner is higher than that of the government.

Rooted in the above simulation analysis results, the system evolution game simulation is carried out in Figure 10. Besides, the array satisfying Situation 1 is simulated 100 times from distinct initial strategy combinations. It is observed that the system only has one stable point E_8, which is consistent with the conclusion derived from Lyapunov's rule.

5. Analysis of the Influence of Technology Transfer Pricing on Evolutionary Game

In the previous section, numerical simulations were used to analyze the influence of each factor on the process and outcome of the evolutionary game based on its effect on the three-party players. In this section, the model will be expanded to predominantly consider the stable strategy (participation, nonparticipation, and participation) and (participation, participation, and nonparticipation) that appeared in cases 2 and 3. In one situation, the company acquires the initial technology for innovation and production, while in the other, it acquires the modified technology for production.

As a significant department that masters the core technology in collaborative innovation, whether the technology transfer of the technology owner can be paid reasonably will become the best approach to influencing the implementation of technological innovation lies in. Accordingly, distinct pricing methods of technology transfer will have various impacts on the evolution of the system and the decision selection of game players. Existing research frequently ignores this key factor [34, 60].

This paper examines the two-part pricing method of technology licensing adopted in technology transfer pricing in the general market, which can be predominantly divided into the *fixed fee*, *variable fee*, and *variable fee + fixed fee* and

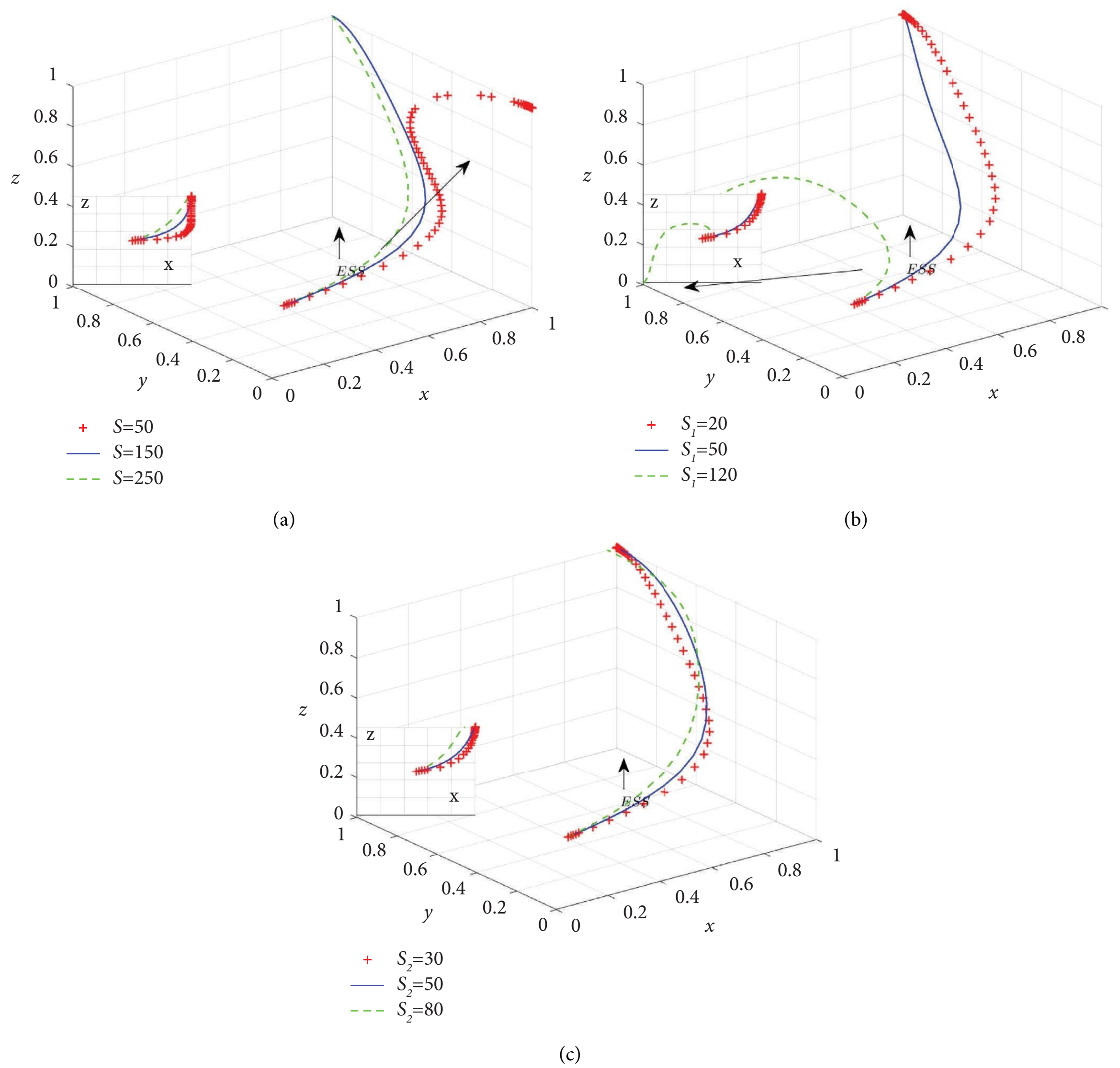


Figure 8: (a) The effect of S on the strategy evolution. (b) The effect of S_1 on the strategy evolution. (c) The effect of S_2 on the strategy evolution.

other various combinations [61–64]. Our pricing strategy is not identical to the two-part pricing strategy. Considering that the technology owner's private technology comes from the silent cost paid in the early stage, we take F_1 as a fixed part of the technology transfer price. We consider a linear pricing strategy for technologies. The cost of the technology owner's innovation (C_3), the firm's benefits (r_4), and the government's benefits (R_1/bR_1) are employed as the pricing basis to analyze the impact of divergent technology transfer pricing methods on the final evolution game.

5.1. Analysis of the Influence of Cost-Based Pricing on Evolutionary Game. First, the technology is priced from the perspective of the technology owner, with the technology royalty being calculated based on the investment made by the technology owner in technological innovation. Suppose r is the pricing ratio, the technology transfer price is expressed as $F_2 = F_1 + rC_3$. To satisfy the participation constraints of the technology owner, the pricing ratio should satisfy $r > 1$.

First, in the case of fixed pricing ratio ($r = 1.5$), the pricing base C_3 is changed for simulation analysis, as demonstrated in Figure 11(a). As the party of payment of technology royalty, the participation probability of the firm is probable to be affected with greater frequency by the change of C_3. When the C_3 is low ($C_3 = 20$), the technology royalty required by the firm is likewise relatively low. Accordingly, the firm will eventually choose not to participate in collaborative innovation. Besides, the final evolutionary strategy is (*participation, nonparticipation, and participation*).

With the increase of C_3, the price of technology transfer will rise, contributing to the need for the firm to purchase technology at a higher price and pay the penalty for breach of contract. Thus, the firm prefers to participate in collaborative innovation. Their willingness to participate will be enhanced

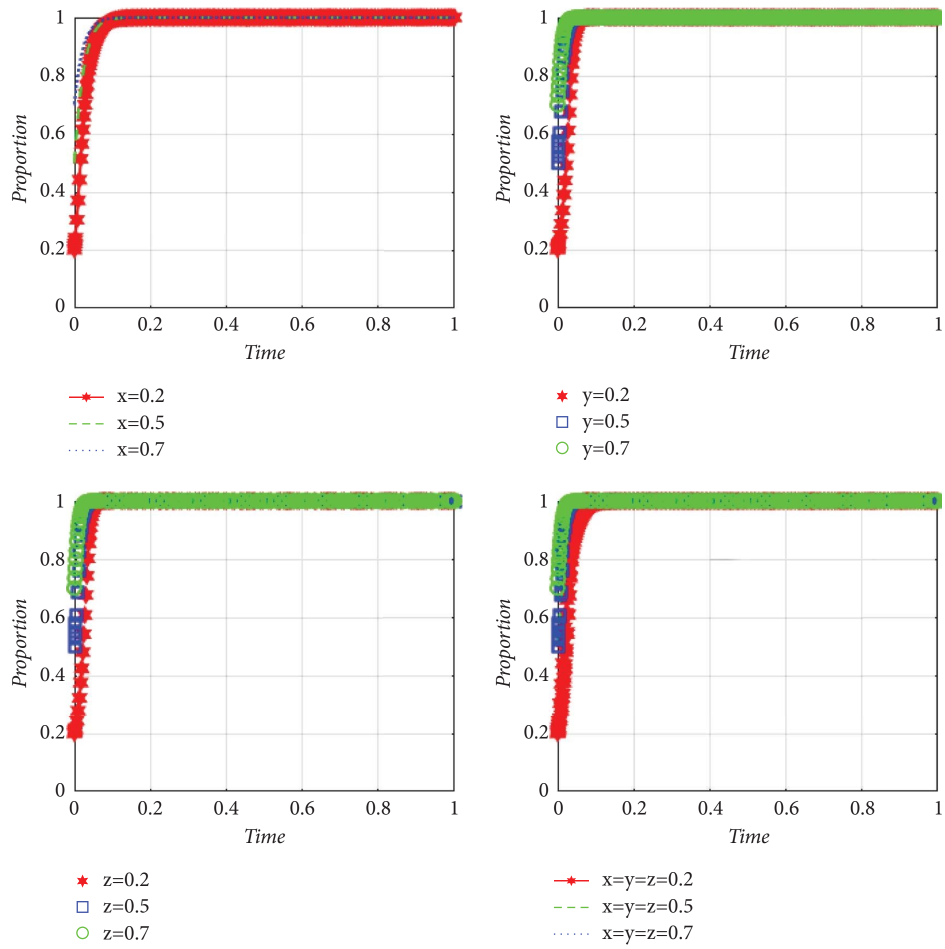


FIGURE 9: Evolution trajectory of the tripartite game under x, y, z change.

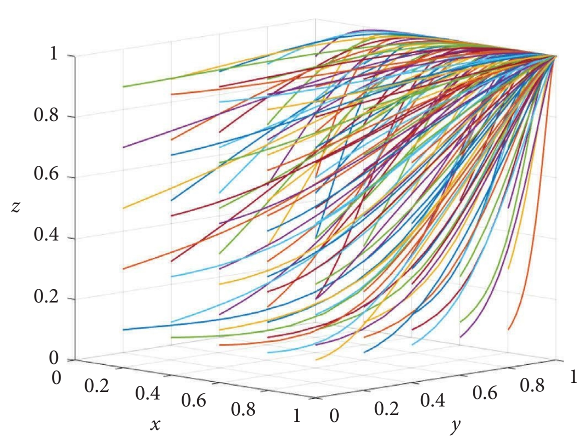


FIGURE 10: The result of 50 times evolutions of array 1.

with the increase of C_3. Likewise, the cost of the technology owner can also be reasonably compensated ($r > 1$). In the end, both the business and the owner of the technology prefer to engage in collaborative technological innovation and the system converges to the equilibrium point E_8.

Next, we conduct a simulation analysis of the pricing ratio r in Figure 11(b). When the pricing ratio is low ($r = 1, 1.3$), the price of technology acquisition is relatively low. The company will decline participation in collaborative innovation. In this case, the system stability point is E_6. Through further simulation analysis, it is obvious that only when r is large enough, the firm will choose to participate in collaborative innovation. In practice, the pricing ratio cannot be extremely high, and consequently the stable evolutionary strategy of the system is (*participation, nonparticipation,*

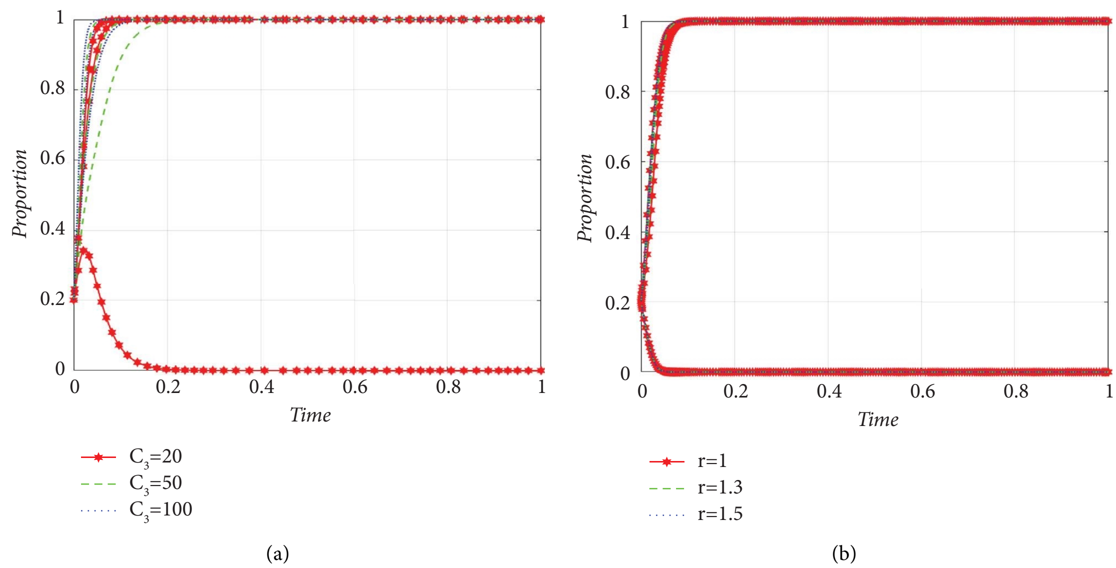


FIGURE 11: (a) The effect of C_3 on the strategy evolution. (b) The effect of r on the strategy evolution.

and participation). After innovation has been completed, it is more prudent for the company to directly decide to acquire the technology.

5.2. Analysis of the Influence of Firm Benefit-Based Pricing on Evolutionary Game. Calculating the technology price in accordance with r_4 after the utilization of innovative technology is definitely to price from the perspective of the firm. The technology transfer price is expressed as $F_2 = F_1 + rr_4$. In the first place, we take the pricing ratio $r = 0.5$ and conduct a simulation analysis on the pricing base r_4 in Figure 12(a).

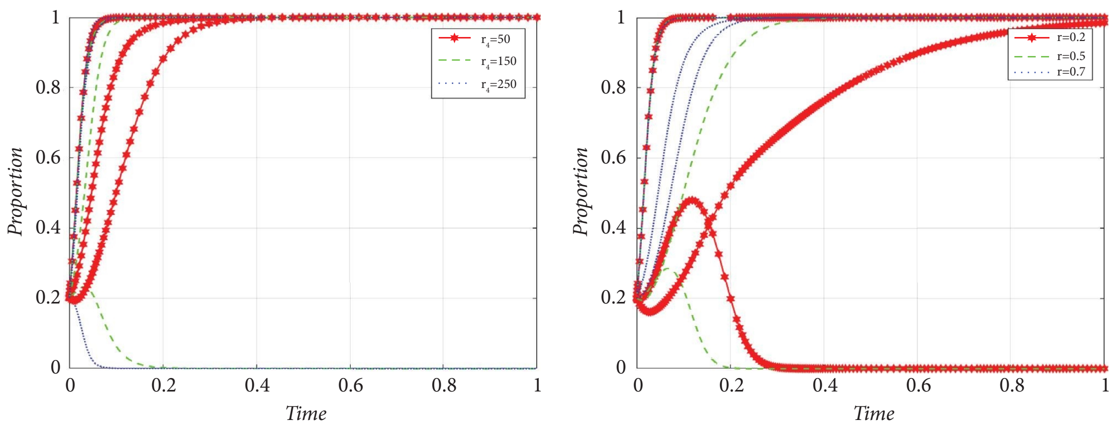
The firm's willingness to participate is more sensitive to the change of r_4. When the benefits are relatively low, companies tend to engage in collaborative innovation in order to obtain cost-reduction subsidies. Nonetheless, when the benefits are relatively high, the firm will choose not to participate in collaborative innovation. Besides, the final evolution trend is $y = 0$. Participation in collaborative innovation enables the owner of the technology to obtain additional benefits and avoid penalties. The evolutionary strategy eventually tends to the balance point E_6.

With the increase in the pricing ratio, the government's willingness to participate slightly weakens, and yet it still chooses to participate in collaborative innovation in the end (Figure 12(b)). On the condition that the pricing ratio is low ($r = 0.2$), the firm can obtain the initial technology at a lower price. That is, it can obtain higher earnings without participating in collaborative innovation. Thus, the firm will not prefer to participate in technological innovation. In the final evolution, with the increase of the pricing ratio ($r = 0.7$), the firm is required to pay a higher technology royalty, and consequently, it will tend to participate in technological innovation.

Consequently, when r_4 are considered as the pricing base of technology royalty, the pricing ratio predominantly affects the decision-making of the firm. On the condition that the pricing ratio is low, the stable strategy of system evolution is (*participation, nonparticipation, and participation*). It implies that it is preferable for the company to purchase the final technology directly. When the pricing ratio is high, the stable strategy of system evolution is (*participation, participation, and participation*). Both the firm and the owner of the technology will elect to participate in technological innovation.

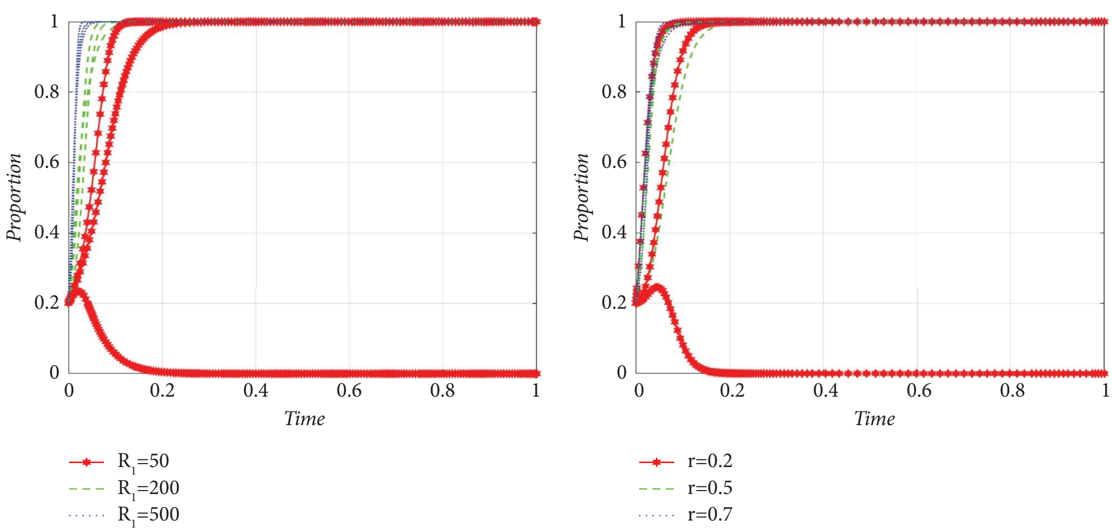
5.3. Analysis of the Influence of Government Benefit-Based Pricing on Evolutionary Game. Since public technology innovation ultimately brings about the improvement of public interests, it is more appropriate to base technology transfer pricing on the benefits of the public sector as represented by the government. Under the condition of government participation, the technology transfer price is expressed as $F_2 = F_1 + rR_1$. Besides, under the condition of government participation, the technology transfer price is expressed as $F_2 = F_1 + rbR_1$. The simulation analysis was carried out by readjusting the replication dynamic equation.

Take the middle value of the pricing rate $r = 0.5$ to conduct a simulation analysis of the pricing benefits in Figure 13(a). When R_1 is relatively low, the government will choose not to take part in collaborative innovation. With the increase of R_1, the probability of government participation will gradually increase. In the meantime, the firm's willingness to participate in collaborative innovation keeps rising. For the technology owner, despite the improvement of R_1 indicates more technology royalties, its participation in collaborative innovation can bring more benefits and avoid punishment. Consequently, increasing the benefits of collaborative innovation can encourage the company and the owner of the technology to engage in collaborative innovation. Besides, the improvement of government benefits also contributes positively to the stability of the system.



(a) (b)

Figure 12: (a) The effect of r_4 on the strategy evolution. (b) The effect of r on the strategy evolution.



(a) (b)

Figure 13: (a) The effect of R_1 on the strategy evolution. (b) The effect of r on the strategy evolution.

When the pricing rate is low ($r = 0.2$), the firm can attain the technology at a reasonable cost. In this case, the firm can obtain more benefits if it does not participate in collaborative innovation (Figure 13(b)). With the increase in pricing, the company must incur greater expenses to use the technology, while the advantages of participating in collaborative innovation are enhanced. As a result, the firm's strategy changes from participation to nonparticipation. Moreover, it can be found that the change in pricing rate predominantly affects the evolution strategy of the firm. Hence, adjusting the pricing rate can promote the participation of the firm in collaborative innovation.

If government benefits are regarded as the pricing base of technology royalty, the government's benefits increased through technology innovation can encourage the company and the owner of the technology to participate in collaborative technology innovation and form a stable state of win-win between the three parties in the end.

Divergent from previous studies, we found that technology transfer pricing has an essential impact on the collaborative innovation process of public technology, the setting of distinct pricing basis and pricing proportion, and ultimately, it influences the willingness of game participants to take part.

6. Conclusion and Policy Recommendations

Under the premise that all game players are bounded rationality, in accordance with the technology collaborative innovation problem in the public domain, this paper constructs a game model of the behavioral strategy evolution of three participants, the government, the firm, and the technology owner. The influence of distinct behavior strategy choices on technology innovation in the technology collaborative innovation system is systematically analyzed. In addition, the influencing factors and evolutionary path of strategy selection, as well as verifying the rationality of the model by simulation were analyzed in this study. It is worth mentioning that we consider the technology transfer in collaborative innovation and focus on the impact of the technology transfer pricing method on the collaborative innovation system. The primary findings of the research are as follows:

(1) The advancement of the benefits of collaborative innovation could motivate the firm and the technology owner to participate in collaborative innovation and achieve win-win cooperation. Compared with the technology owner, the firm is more attuned to changes in benefits. Unsatisfactory benefits of cooperation are easy to induce opportunistic behavior, which is not conducive to the integration of technology resources. Particularly for benefit-oriented firms, benefits, and participation willingness can have a double-sided promoting impact.

(2) Cost and benefit allocation coefficient will affect the stability of the public technology collaborative innovation system. If the cost allocation coefficient is low, the firm will be more willing to participate. As the increase of cost allocation coefficient, the willingness of the technology owner to participate will incrementally increase. During the same time, the willingness of the firm to participate will incrementally decrease. This indicates that the cost allocation will affect the stability of the collaborative innovation system. In addition, the party that bears more costs has less to gain, which contributes to a lower willingness to participate. The evolutionary strategies of both the firm and the technology owner are sensitive to changes in the allocation coefficients of costs and benefits. The scientific configuration of the cost and benefit allocation coefficient is conducive to maintaining the system's stability and the players' cooperation.

(3) Punishment plays an important role in collaborative innovation. When the intensity of punishment is relatively low, the willingness of both the technology owner and the firm will decrease accordingly. With the increase in the intensity of punishment, there is a corresponding increase in their willingness to participate, and alterations in the intensity of punishment can result in rapid fluctuations in their willingness to participate. By contrast, the firm is more sensitive to the intensity of punishment than the technology owner. Large default costs or prices can effectively restrain the emergence of opportunistic behavior. The government can facilitate collaborative innovation by modifying the severity of punitive rules. Furthermore, incentive measures have distinct impacts on the firm and the technology owner. Besides, the technology owner is more sensitive to government subsidy incentives than the firm. The appropriate level of separate subsidies can maintain the advantages of the technology owner while ensuring the participation effect of the firm. A firm's and the owner of a technology's cooperation in technological innovation can be facilitated by reasonable government subsidies and punishment regulations.

(4) The initial willingness to participate has little influence on the stability of the system as a whole, which implies that no matter what the initial participation state of the game players is, through the manipulation of various influencing factors, improved evolutionary effects can be achieved.

(5) The method of pricing technology transfer is also a significant factor in the evolution process. When technology pricing is in accordance with the technology innovation cost of the technology owner, the firm will choose to participate in collaborative innovation only when the pricing ratio is large enough. In this instance, the company will choose to acquire the technology directly following the completion of the innovation. When technology pricing is built upon the benefits of the firm, the pricing ratio predominantly affects the decision of the firm. On the condition that the pricing ratio is low, the firm will not participate in collaborative innovation and choose to directly acquire the technology after the completion of innovation. If the pricing ratio is high, both the firm and the technology owner will choose to engage in collaborative innovation. When the benefits of the government are taken as the pricing base of technology, the benefits of the government increased through technology innovation can encourage the firm and the technology owner to participate in collaborative technology innovation, and ultimately, the three parties will reach a stable, win-win equilibrium.

To promote the cooperative innovation of public technology, we present several policy recommendations for decision-makers.

(1) A scientific cost and benefit allocation system should be established among the collaborative innovation subjects, and the disclosure should be improved to eliminate the asymmetrical role of information in innovation cooperation. The principle of fairness and matching benefits should be adhered to at all times, and a reasonable mechanism for distributing benefits should be designed after fully considering factors such as the strength, investment, degree of effort, and cost of risk of innovation subjects.

(2) The government should formulate flexible policies according to the internal and external environment of collaborative innovation, including building a scientific reward and punishment system, moderately enhancing the intensity of rewards and sanctions, and adopting a dynamic reward and punishment mechanism. On the one hand, the rational use of policy tools including rewards and penalties or subsidies could make up for the lack of motivation for collaborative innovation between the

firm and the technology owner. On the other hand, it is necessary to use policy tools carefully. The use of policy tools increases the reliance of collaborative innovation subjects on policy tools and impedes the substantial improvement of their collaborative innovation capacity.

(3) Government institutions should establish and enhance the corresponding technology evaluation and transfer mechanism, particularly designing a reasonable technology transfer pricing method to strengthen the transfer of private technology to public technology in the market. Simultaneously, the government must establish a technology cooperation platform, eliminate communication barriers between firms and technology owners, and establish a favorable market environment for public technology collaborative innovation The Technology and Innovation Support Center (TISC) launched by the State Intellectual Property Office of China can enable enterprises and technology owners to speedily grasp industry trends and new technology information, and enhance innovation capabilities.

Despite this study has achieved its intended objectives, deficiencies remain that are worthy of attention. The existence of certain important limitations arising from the basic assumptions of the model is duly recognized and acknowledged, thereby potentially opening doors for future research. In terms of the foundation of technology pricing, the quantification of public benefits into monetary terms was undertaken directly. It is challenging to measure public benefits with money. National defense or military benefits frequently need to be converted into other performance indicators including combat effectiveness for value judgment, and consequently, the relationship between public benefits and currency requires further consideration. Moreover, the research on collaborative innovation of public technology in this paper is predominantly built upon existing private technologies in the market. With a focus on enhancing and revolutionizing current technologies, the emphasis lies on the improvement and innovation of existing technologies. In practical terms, certain public technologies may necessitate research and development (R&D) innovation, thereby providing an avenue for future studies to explore the collaborative dynamics of R&D innovation.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

Authors' Contributions

Y.L. and H.W. conceptualized the study; Y.L. proposed the methodology; Y.L. was responsible for software; Y.L., X.L., and H.W. validated the data; Y.L. performed formal analysis; X.L. investigated the study; X.L. was responsible for resources; Y.L. curated the data; Y.L. prepared the original draft; X.L. and H.W. reviewed and edited the manuscript; H.W. visualized the study; X.L. supervised the study; H.W. administered the project; X.L. acquired the funding. All authors have read and agreed to the published version of the manuscript.

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