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# Evolutionary Game Analysis on Cooperative Behavior of Major Projects' Technology Innovation Subjects under General Contracting Mode

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**Abstract:** Major projects are the important platform for enhancing a country's comprehensive national power and strengthening its capacity for independent innovation. Although major projects in China have made remarkable achievements, willingness to cooperate and innovate has not achieved the desired target. In this paper, the evolutionary game model of cooperative innovation behavior of general contractors and subcontractors is constructed by considering reputational factors. Through theoretical derivation, the influence of the distribution ratio of collaborative innovation benefit, spillover technology absorption capacity, and reputation discounting coefficient on innovation behavior is analyzed. Finally, MATLAB software is used to simulate the dynamic evolution process of strategy selection. The results show that (1) a reasonable benefit distribution coefficient can promote the evolution of innovation behavior in a positive direction; (2) both the reduction of innovation cost and the increase of spillover technology absorption capacity can make the innovation subject more inclined to choose the active collaborative innovation strategy; and (3) it is the higher-than-threshold reputation loss that can effectively inhibit the "free-rider" behavior. The research conclusions and managerial implications can provide reference for improving the willingness to cooperate in major projects' technology innovation.

**Keywords:** general contracting mode; major projects; technology innovation; reputation effect; evolutionary game

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## 1. Introduction

Major projects refer to large-scale public engineering with a large investment scale, long implementation period, and exceptionally complex technology, which exerts far-reaching impacts on economic development, social advancement, and environmental protection [1,2]. At present, China is in a period of economic development transformation, and the completion and operation of major projects such as the Hong Kong-Zhuhai-Macao Bridge and the Beijing-Shanghai High-Speed Railway has played a key role in promoting the development of the national economy. At the same time, it also puts forward a new challenge to the major projects' technology innovation [3,4]. On the one hand, the transformation rate of the results of major projects' technology innovation needs to be further strengthened; on the other hand, the cooperation willingness of each innovation subject is not strong. Although the Chinese government has introduced many incentive policies, the effect of policy implementation is not obvious. Therefore, how to break through the existing technological innovation predicament has become a common topic of concern.

The importance of technology innovation has become more and more prominent in today's world, and it is widely active in various fields, which is a necessary means to achieve high-quality economic development [5]. Different from general technology innovation, major projects' technology innovation involves a complex process, often beyond the boundaries of single organization [6], and it is difficult to deal with the uncertainty in the innovation process by relying only on the innovation of single organization [7]. Therefore, a major project's technology innovation refers to the technological innovation activities carried out by various types of innovation organizations in collaboration [8]. Common ways of major project technology innovation mainly include organization, cooperation, and technology [9,10]. In this process, the new generation of information technology, mainly represented by artificial intelligence, promotes breakthroughs in technology innovation, such as the construction of the Hong Kong-Zhuhai-Macao Bridge undersea tunnel. As major projects involve many stakeholders, high complexity, and uncertainty, project risk has become a major challenge for technology innovation. Based on this, scholars have established the risk propagation model based on multi-layer heterogeneous networks to deeply analyze the multiple uncertainties in the process of the technological innovation of major projects [11]. It is worth noting that various types of innovation organizations are temporary cooperative relationships [12], which are prone to conflicts of interest and resources, breeding opportunistic behaviors and thus reducing the efficiency of cooperation [13,14]. Based on this, some scholars believe that the construction of a major engineering technology innovation consortium can effectively alleviate the occurrence of the above problems [15]. The premise is that the technology innovation behaviors of the various types of innovation organizations in the innovation consortium remain consistent.

On the topic of innovation behavior choice, many scholars have conducted extensive research on it. For example, Zan et al. [16] constructed an evolutionary game model of industry–university–research cooperation and innovation and analyzed the cooperative relationship between enterprises, universities, and research institutes as well as the influence of government policies on cooperative innovation, while Ma et al. [17] constructed an evolutionary game model of technological innovation cooperation network and investigated the influence of different government policies (subsidies, tax incentives, and intellectual property rights protection) on the innovation behaviors. In view of the complexity of technology innovation in major projects, the traditional innovation paradigm is no longer suitable for the study of technology innovation in major projects due to unclear responsibilities and rights, poor information communication, etc. [18]. Innovation networks and ecosystems are gradually introduced into the study of technology innovation in major projects, and innovation networks and ecosystems are likewise gradually introduced into the process of major projects' technology innovation. In the innovation network, each subject can carry out technological innovation activities and create value together [19], but the subjects may have different goals and plans from those of major projects' technological innovation, so the leader of the innovation network should play an active role in facilitating. Previous studies have mostly explored major projects' technology innovation from the perspective of qualitative analysis, and from the perspective of quantitative analysis, they have mostly taken industry–academia–research as the main objects of study and lacked the consideration of the reputation factor. In this paper, based on the topic of behavioral choice of the main subjects of technology innovation in major projects and considering the reputation factor, an evolutionary game model consisting of general contractors and subcontractors is built. More specifically, we focused on the following questions: (1) What factors can affect the technology innovation enthusiasm of general contractors and subcontractors, and what are their effects? (2) How does the reputation factor influence the innovative behavioral choices of general contractors and subcontractors? (3) How do general contractors and subcontractors influence each other in the process of technology innovation?

The main contributions of this paper are as follows: (1) We have taken the general contractor and subcontractor as the research objects, constructed an evolutionary game model for the evolution of the behavior of the main subjects of technology innovation in major projects, and analyzed the change process of the choice of collaborative innovation behavior of different decision-making groups. The research objects in the existing literature mainly focus on the government, owners, industry, academia and research, and enterprises, which broadens the research paradigm. (2) We incorporated the reputation factor into the game model, which is rarely mentioned in previous studies.

The arrangement of the remaining sections is as follows: Section 2 summarizes and analyses the existing literature from two aspects: major projects' technology innovation and evolutionary game theory. Section 3 focuses on the background of the research problem and puts forward some assumptions. Section 4 is based on the payment matrix, the payoff functions, and replication dynamic equations under different strategies, and it judges the stability of each equilibrium point. In Section 5, MATLAB software is used to simulate the dynamic evolution process of strategy selection, and the influence of related factors is described intuitively from the initial probability, income distribution ratio, the absorption capacity of spillover technology, etc. Finally, conclusions, managerial implications, and limitations and future research directions are drawn in Section 6.

## 2. Literature Review

### *2.1. Major Projects' Technology Innovation*

In recent years, major projects, as represented by the Hong Kong-Zhuhai-Macao Bridge, have made outstanding contributions to China's economic development and the development of people's livelihoods and provided an important platform for technology innovation in the industry [3]. However, under highly uncertain engineering environments, diversified engineering needs, and increasingly demanding engineering objectives, the construction of major projects is facing increasing challenges [19,20]. Technology innovation is an inevitable choice to solve construction problems. As a paradigm for unlocking high-tech and economic opportunity, technology innovation can effectively improve the efficiency of existing technologies [21] and is an important means of promoting socio-economic development [22]. Different from general technology innovation, major projects' technology innovation is a technological innovation activity carried out by all kinds of technological innovation subjects around the engineering demand with major projects as the carrier, and it is the integration process of technological innovation results, with the characteristics of target constraints, organizational synergies, and process complexity [23].

At present, the research on the technological innovation of major projects mainly focuses on the influencing factors, behavior of the innovation subject, and a case study. As a special class of construction products, its technological innovation is affected by a variety of factors. For example, Manley [24] suggested that in the process of technology innovation, owners can greatly influence and motivate technological innovation activities. At the same time, owners with strong leadership will enhance this influence [25]. Expected profitability is the main driver of technology innovation, especially in profit-oriented major projects [26]. Due to the large number of stakeholders in major projects and the complexity of their co-operative relationships, it was found that good, cooperative relationships contribute to the success of technological innovation activities [27]. Ozorhon and Oral [28] found that project complexity, innovation policy, and environmental sustainability are the main drivers of innovation in construction engineering projects. In addition to this, factors such as resource integration capacity [29], innovation silo phenomenon [30], and knowledge transfer effectiveness [31] affect major engineering technology innovation activities to a certain extent. With the depth of research, scholars have found that the behavioral choices of the main body of major engineering technology innovation have a significant impact on the final innovation effectiveness. The research shows that a reasonable distribution ratio of innovation benefits, a high degree of cooperation and trust, and perfect government incentives and penalties can promote the behavior of the main body of innovation to change in a positive direction, which in turn makes the technological innovation successful [32–34]. In this research process, scholars mostly construct evolutionary game models to study the influence of coefficients such as government policies [17], R&D costs [35], revenue distribution coefficients, and willingness [36] to cooperate on the behavioral choices of innovation subjects. In addition, case studies can provide builders with valuable practical experience and decision-making reference by studying actual major engineering construction problems. For example, Brockmann et al. [37] conducted a case study on the technological innovation of Thailand's Manna Expressway and found that innovations in engineering structures, materials, methods, and equipment are crucial to completing major engineering construction on time and improving its quality. Qin and Gao [38] described the research progress of multifunctional composite bridge construction technology in China and the innovations of new bridges and composite bridge structures and then concluded that China has made progress in the research of multifunctional composite bridge construction technology and the innovation of new bridges and composite bridge structures and practices, which led to the conclusion that China has gradually developed key technologies for large-span highway bridges with Chinese characteristics. Kattel et al. [39], using the South–North Water Diversion Project in China as an example, argued that the provision of improved water infrastructure technologies and innovations can address the challenges posed by water scarcity to environmental sustainability.

### 2.2. Evolutionary Game Theory

Evolutionary game theory originated from Darwin's biological evolution theory of "natural selection, survival of the fittest" and plays one of the most important roles in terms of mathematically dealing with human intentions. It is often used to study the interactions between different players or groups of players, and its main idea is to find the frequency of the strategies adopted by groups of people in the process of evolutionary games [40].

Currently, the main areas of research closely related to evolutionary game theory include manufacturing and supply chain. In the field of manufacturing, evolutionary game theory can provide rich dynamic insights into the interactions between firms, so it is widely used in manufacturers' production decision-making problems [41]. By considering different influencing factors and selecting different decision-making subjects, scholars have constructed different types of evolutionary game models, such as two-party [42] and three-party game models [43]. Clearly, enterprises have a strong memory when making decisions, and the next stage of decision making depends not only on the current state but also on the historical state, so scholars built the Stackelberg model [44]. However, fractional-order theory can directly reflect the "memory characteristics" of variables, and the construction of fractional-order evolutionary game model is closer to reality [45]. Unlike manufacturing, the application of evolutionary game theory in the supply chain emphasizes the influence of market factors on their own income and the overall profit of the supply chain. For example, Qian et al. [46] investigated the effects of consumer preferences and government subsidies on the decision-making behavior of the green building material supply chain. In the study of major projects, constructing evolutionary game models to explore the stabilization strategies of game subjects is a common research paradigm. For example, Zan et al. [16] constructed an evolutionary game model of industry–university–research cooperation and innovation and analyzed the cooperative relationship between enterprises and research and the influence of government policies on the stability of industry–university–research cooperation and innovation. Yi and Hiroatsu [47] constructed a three-party evolutionary game model consisting of government, construction firms, and universities to explore the dynamic evolution of RAAC's innovation strategy choices. In addition to the above research streams, evolutionary game theory has also been applied to the study of human life saving [48], human cooperation [49], mobile health [50], emergency management [51], green management [52], and so on.

### 2.3. Literature Commentary

Existing studies on major projects' technology innovation and evolutionary game theory have laid a solid theoretical foundation for our work. More specifically, (1) in terms of major projects' technology innovation, the influencing factors, innovation subjects' behavior, and case studies have received the most attention from scholars, and the research method is mainly based on qualitative analysis. Most of the subjects comprise two or three parties from the government, owners, industry, academia, research, and enterprises, and few scholars consider the cooperative behavior between general contractors and subcontractors. (2) in the application of evolutionary game theory, few scholars have included the reputation factor into the evolutionary game model and explored the influence of the reputation factor on the evolutionary results. Therefore, in order to solve the major engineering construction problems and improve the output benefits of technological innovation, this study considers the reputation factor, establishes an evolutionary game model consisting of general contractors and subcontractors, analyzes the trend of the behavior of the innovation subjects, and dynamically portrays the impact of the influencing factors (innovation benefit distribution coefficient, spillover technology absorption capacity, and reputation discount coefficient) on the behavioral choices of the innovation subjects. The study broadens the research paradigm of major projects' technology innovation, analyzes in depth the driving forces of major projects' technology innovation, and proposes more appropriate managerial implications for the future.

## 3. Problem Description and Assumptions

### 3.1. Problem Description

The general contracting mode of engineering construction projects is a contracting mode adopted by the owner to achieve project construction goals, such as the Changsha Maglev F-track technology innovation project in China. Major projects' technology innovation takes the breakthrough of core technology as its own responsibility, and the active cooperation of all kinds of innovation organizations is a key step to ensure the success of technology innovation. At the same time, how various innovation organizations can choose strategies that are beneficial to their own interests in the innovation process is a complex issue. In this process, since all kinds of innovation organizations are limited, rational decision makers, their initial decisions cannot reach the optimal level, and they need to learn and adjust continuously to achieve the optimal strategy. The evolutionary game model can illustrate the dynamic change process of decision-making behavior from a micro perspective, so it is feasible to use the evolutionary game model.

### 3.2. Model Assumptions

This paper constructs an evolutionary game model consisting of two decision-making groups: general contractors and subcontractors. Since the above two groups are finite and rational, they need to go through many games to achieve the optimal decision. To facilitate the analysis, the following assumptions are made:

**Assumption 1.** *In the process of technology innovation, with profit maximization as the decision-making goal, general contractors can choose two strategies, i.e., active collaborative innovation and negative collaborative innovation, and the probabilities are $x$, $1 - x$ $(0 \leq x \leq 1)$ respectively. The active collaborative innovation shows that general contractors are willing to carry out efficient collaborative innovation with subcontractors. The negative collaborative innovation shows that they only want to obtain others' technical achievements.*

**Assumption 2.** *From the perspective of maximizing their own benefits, subcontractors can choose two strategies: active collaborative innovation and negative collaborative innovation, with probabilities of $y$, $1 - y$ $(0 \leq y \leq 1)$. Active collaborative innovation means that they actively participate in technology research and development and collaborative innovation, whereas negative collaborative innovation refers to unwillingness to devote themselves to technology research and development.*

**Assumption 3.** *The basic income of general contractors and subcontractors is $R_1$ and $R_2$. When two entities both chooseactive collaborative innovation, they will obtain collaborative innovation benefit $M$. However, when one entity adopts the negative collaborative innovation strategy, the collaborative innovation benefit $M$ is zero. Because general contractors are in a dominant position, they have the right to distribute the collaborative innovation benefit, and the assumption $\lambda$ $(0 < \lambda < 1)$ indicates the distribution ratio. In addition, the technological income generated in the collaborative process is $\eta_i V_i$ $(i = 1, 2)$.*

**Assumption 4.** *The of collaborative innovation has the characteristics of dynamic replacement, which is characterized by the dynamic changes between temporary alliances or permanent organizations, and the technological achievements of collaborative innovation are finally transferred to general contractors after the contract contents signed in the early stage are satisfied. Because the innovative technological achievements cannot be completely transformed, this paper assumes that the conversion rate of technological achievements is $\beta$ ($0 < \beta < 1$).*

**Assumption 5.** *When general contractors and subcontractors carry out technology innovation, they need to invest their own innovation costs $C_i$ ($i = 1, 2$). According to the reality, both general contractors and subcontractors have the capability to absorb the existing knowledge and technology. It is assumed that $\alpha_1$ and $\alpha_2$ represent the spillover technology absorption capacity of the general contractor and subcontractor, so the reduced innovation cost can be expressed as $\alpha_i C_i$ ($i = 1, 2$).*

**Assumption 6.** *When one entity chooses negative collaborative innovation, it can absorb the knowledge and technology of the other side in the innovation process. Suppose that the income obtained by absorbing each other's knowledge and technology is $\rho_i V_j$ ($i, j = 1, 2, i \neq j$). If the negative collaborative innovation is discovered, it will cause certain reputation loss. Assuming that the probability of being discovered is p, the lost reputation gain is $S_i = 0.5pqb_i^2$ ($i = 1, 2$).*

The related parameters and their definitions are shown in Table 1.

**Table 1.** Model parameters and their definitions.

| Parameters | Definitions | Initial Condition |
|---|---|---|
| $R_1$ | Basic income of general contractors | |
| $R_2$ | Basic income of subcontractors | |
| M | Collaborative innovation benefit | |
| $\lambda$ | Distribution ratio of collaborative innovation benefit | |
| $\eta_i$ | Technical innovation output coefficient | |
| $V_i$ | Knowledge and technical value | (1) $0 < \lambda, \beta < 1$ |
| $\beta$ | Conversion rate of technological achievements | (2) $\rho_i > V_j$ ($i, j = 1, 2, i \neq j$) |
| $C_i$ | Innovation costs | |
| $\alpha_i$ | Spillover technology absorption capacity coefficient | |
| $\rho_i$ | Entities' learning ability | |
| p | Probability of being discovered | |
| q | Reputation discount coefficient | |
| $b_i$ | Negative level | |

## 4. Model Construction and Solution

### *4.1. Model Building*

Based on Section 3.2, the payment matrix can be obtained, as shown in Table 2. Suppose that average income is $E_{ij}$, and the expected income is $E_i$. i represents each entity, and $i \in \{1, 2\}$ (1 and 2, respectively, represent general contractors and subcontractors), while j represents the strategy choice, and $j \in \{1, 2\}$ (1 and 2, respectively, represent active collaborative innovation and negative collaborative innovation).

**Table 2.** Payment matrix of general contractors and subcontractors.

| | Payment Matrix | General Contractors: Active Collaborative Innovation | General Contractors: Negative Collaborative Innovation |
|---|---|---|---|
| Subcontractors | Active collaborative innovation | $R_1 + \eta_1 V_1 + (1 - \lambda + \beta)M - (1 - \alpha_1)C_1$<br>$R_2 + \eta_2 V_2 + \lambda M - (1 - \alpha_2)C_2$ | $R_1 + \rho_1 V_2 - \frac{1}{2}pqb_1^2$<br>$R_2 + \eta_2 V_2 - (1 - \alpha_2)C_2 - \rho_1 V_2$ |
| Subcontractors | Negative collaborative innovation | $R_1 + \eta_1 V_1 - (1 - \alpha_1)C_1 - \rho_2 V_1$<br>$R_2 + \rho_2 V_1 - \frac{1}{2}pqb_2^2$ | $R_1 - \frac{1}{2}pqb_1^2$<br>$R_2 - \frac{1}{2}pqb_2^2$ |

According to Table 2, the average income and expected income of general contractors can be expressed as follows:

$$E_{11} = y[(1-\lambda+\beta)M + \rho_2 V_1] + R_1 + \eta_1 V_1 - (1-\alpha_1)C_1 - \rho_2 V_1 \tag{1}$$

$$E_{12} = y\rho_1 V_2 + R_1 - \frac{1}{2}pqb_1^2 \tag{2}$$

$$E_1 = xy[(1-\lambda+\beta)M + \rho_2 V_1 - \rho_1 V_2] + y\rho_1 V_2 + x\left[\eta_1 V_1 - (1-\alpha_1)C_1 - \rho_2 V_1 + \frac{1}{2}pq{b_1}^2\right] + R_1 - \frac{1}{2}pq{b_1}^2 \tag{3}$$

The average income and expected income of subcontractors are, respectively, shown in Equations (4)–(6).

$$E_{21} = x(\lambda M + \rho_1 V_2) + R_2 + \eta_2 V_2 - (1-\alpha_2)C_2 - \rho_1 V_2 \tag{4}$$

$$E_{22} = x\rho_2 V_1 + R_2 - \frac{1}{2}pqb_2^2 \tag{5}$$

$$E_2 = xy[\lambda M + \rho_1 V_2 - \rho_2 V_1] + x\rho_2 V_{21} + R_2 - \frac{1}{2}pq{b_2}^2 y\left[\eta_2 V_2 - (1-\alpha_2)C_2 - \rho_1 V_2 + \frac{1}{2}pq{b_2}^2\right] \tag{6}$$

According to the Malthusian dynamic equation [53], the replicated dynamic equations of each entity are shown in Equations (7) and (8).

$$F(x) = \frac{dx}{dt} = x(1-x)\left[y(1-\lambda+\beta)M + y(\rho_2 V_1 - \rho_1 V_2) + \eta_1 V_1 + \frac{1}{2}pqb_1^2 - (1-\alpha_1)C_1 - \rho_2 V_1\right] \tag{7}$$

$$G(y) = \frac{dy}{dt} = y(1-y)\left[x\lambda M + x(\rho_1 V_2 - \rho_2 V_1) + \eta_2 V_2 + +\frac{1}{2}pqb_2^2 - (1-\alpha_2)C_2 - \rho_1 V_2\right] \tag{8}$$

*4.2. Model Analysis*

The evolutionary game between general contractors and subcontractors can be described by a two-dimensional dynamic system composed of differential Equations (7) and (8). Let $\frac{dx}{dt} = 0$ and $\frac{dy}{dt} = 0$; the local equilibrium points of two-dimensional dynamical system can be obtained, which are $Q_1(0, 0)$, $Q_2(0, 1)$, $Q_3(1, 0)$, $Q_4(1, 1)$, and $Q_5(x^*, y^*)$:

$$x^* = \frac{2\rho_1 V_2 + 2(1-\alpha_2)C_2 - pqb_2^2 - 2\eta_2 V_2}{2(\lambda M + \rho_1 V_2 - \rho_2 V_1)}$$

$$y^* = \frac{2\rho_2 V_1 + 2(1-\alpha_1)C_1 - pqb_1^2 - 2\eta_1 V_1}{2[(1-\lambda+\beta)M + \rho_2 V_1 - \rho_1 V_2]}$$

According to Friedman's method [54], the Jacobian matrix of dynamical system is

$$J = \begin{vmatrix} J_{11} & J_{12} \\ J_{21} & J_{22} \end{vmatrix} = \begin{vmatrix} \frac{(dx/dt)}{dx} & \frac{(dx/dt)}{dy} \\ \frac{(dy/dt)}{dx} & \frac{(dy/dt)}{dy} \end{vmatrix} \tag{9}$$

where

$$\frac{(dx/dt)}{dx} = (1-2x)\left[y(1-\lambda+\beta)M + y\rho_2 V_1 - y\rho_1 V_2 + \eta_1 V_1 + \frac{1}{2}pqb_1^2 - (1-\alpha_1)C_1 - \rho_2 V_1\right]$$

$$\frac{(dx/dt)}{dy} = x(1-x)[(1-\lambda+\beta)M + \rho_2 V_1 - \rho_1 V_2]$$

$$\frac{(dy/dt)}{dx} = y(1-y)\lambda M + \rho_1 V_2 - \rho_2 V_1$$

$$\frac{(dy/dt)}{dy} = (1-2y)\left[x\lambda M + x\rho_1 V_2 - x\rho_2 V_1 + \eta_2 V_2 + \frac{1}{2}pqb_2^2 - (1-\alpha_2)C_2 - \rho_1 V_2\right]$$

The stability of equilibrium points can be determined by the sign of the determinant and trace of the Jacobian matrix. When Det(J) > 0 and Tr(J) < 0, the equilibrium points are evolutionary stable strategies. In order to ensure that $x^*$, $y^*$ are all on the $R = \{(x, y) | 0 \leq x \leq 1, 0 \leq y \leq 1\}$ plane, the above assumptions must meet the following:

$$\eta_i V_i + \frac{1}{2}pqb_i^2 - (1-\alpha_i)C_i - \rho_j V_i < 0, (i, j = 1, 2 \text{ and } i \neq j)$$

$$\lambda M - \rho_2 V_1 + \eta_2 V_2 + \frac{1}{2}pqb_2^2 - (1-\alpha_2)C_2 > 0$$

$$(1-\lambda+\beta)M - \rho_1 V_2 + \eta_1 V_1 + \frac{1}{2}pqb_1^2 - (1-\alpha_1)C_1 > 0$$

There are five local equilibrium points in the system, $Q_1(0, 0)$, $Q_2(0, 1)$, $Q_3(1, 0)$, $Q_4(1, 1)$, and $Q_5(x^*, y^*)$, and the stability of each equilibrium point is shown in Table 3.

**Table 3.** Stability of each equilibrium point.

| Order | Equilibrium Point | Det(J) | Tr(J) | Stability |
|---|---|---|---|---|
| 1 | $Q_1(0, 0)$ | + | - | Asymptotic stable point |
| 2 | $Q_2(0, 1)$ | + | + | Instability point |
| 3 | $Q_3(1, 0)$ | + | + | Instability point |
| 4 | $Q_4(1, 1)$ | + | - | Asymptotic stable point |
| 5 | $Q_5(x^*, y^*)$ | - | 0 | Saddle point |

From Table 3, for the asymptotic stable point $Q_1(0, 0)$, $Q_4(1, 1)$, the evolution strategies are {negative collaborative innovation, negative collaborative innovation} and {active collaborative innovation, active collaborative innovation}. $Q_2(0, 1)$ and $Q_3(1, 0)$ are the instability points for the system to converge different strategies, and $Q_5(x^*, y^*)$ is the saddle point. Figure 1 shows the phase distribution of cooperative evolutionary game between general contractors and subcontractors.

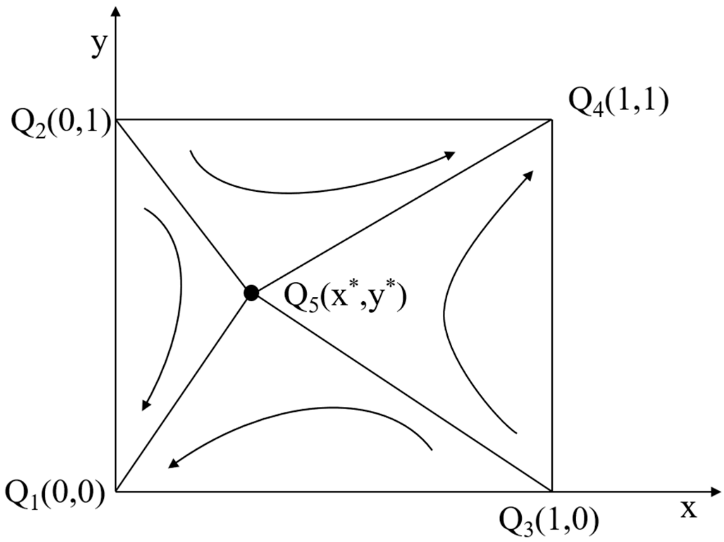


**Figure 1.** Phase diagram of cooperation evolutionary game.

From the curve trend in Figure 1, when the initial state is located on the upper right corner of the broken line connection ($Q_2Q_5Q_3Q_4$), the system will gradually converge to $Q_4(1, 1)$; that is, general contractors and subcontractors evolve to select the strategy of active collaborative innovation. Similarly, when located in the lower left corner of the broken line connection ($Q_2Q_5Q_3Q_1$), the system will gradually converge to $Q_1(0, 0)$; that is, general contractors and subcontractors will choose the negative collaborative innovation strategy. Which stable state the system evolves towards depends on the regional area $Q_2Q_5Q_3Q_4(S_1)$ and the size of the regional area $Q_2Q_5Q_3Q_1(S_2)$. When $S_1$ is the larger area, the probability is greater that both entities will move towards {active collaborative innovation, active collaborative innovation}. However, when $S_2$ is the larger area, the probability is greater that both entities will move towards {negative collaborative innovation, negative collaborative innovation}. It can be determined that $S_2$ is as follows:

$$S_2 = \frac{1}{2}(x^* + y^*) = \frac{2\rho_1 V_2 + 2(1-\alpha_2)C_2 - pqb_2^2 - 2\eta_2 V_2}{\lambda M + \rho_1 V_2 - \rho_2 V_1} + \frac{2\rho_2 V_1 + 2(1-\alpha_1)C_1 - pqb_1^2 - 2\eta_1 V_1}{(1-\lambda+\beta)M + \rho_2 V_1 - \rho_1 V_2} \tag{10}$$

The main factors affecting the change of the area $S_2$ are discussed below.

**Proposition 1.** *The influence of distribution ratio of collaborative innovation benefit on the final decision making of general contractors and subcontractors depends on specific conditions.*

**Proof.** The following can be derived from Equation (10):

$$\frac{\partial S_2}{\partial \lambda} = \frac{M\left[2\rho_2 V_1 + 2(1-\alpha_1)C_1 - pqb_1^2 - 2\eta_1 V_1\right]}{\left[(1-\lambda+\beta)M + \rho_2 V_1 - \rho_1 V_2\right]^2} - \frac{M\left[2\rho_1 V_2 + 2(1-\alpha_2)C_2 - pqb_2^2 - 2\eta_2 V_2\right]}{(\lambda M + \rho_1 V_2 - \rho_2 V_1)^2} \tag{11}$$

According to the above, the distribution coefficient of $\frac{\partial S_2}{\partial \lambda}$ and the total yield of collaborative innovation is not a monotonic function, and the value of $\frac{\partial S_2}{\partial \lambda}$ should be determined according to the specific situation. Let $\frac{\partial S_2}{\partial \lambda} = 0$; we thus obtain the following:

$$\frac{\left[2\rho_2 V_1 + 2(1-\alpha_1)C_1 - pqb_1^2 - 2\eta_1 V_1\right]}{\left[(1-\lambda+\beta)M + \rho_2 V_1 - \rho_1 V_2\right]^2} = \frac{\left[2\rho_1 V_2 + 2(1-\alpha_2)C_2 - pqb_2^2 - 2\eta_2 V_2\right]}{(\lambda M + \rho_1 V_2 - \rho_2 V_1)^2} \tag{12}$$

When $\frac{\left[2\rho_2 V_1 + 2(1-\alpha_1)C_1 - pqb_1^2 - 2\eta_1 V_1\right]}{\left[(1-\lambda+\beta)M + \rho_2 V_1 - \rho_1 V_2\right]^2} > \frac{\left[2\rho_1 V_2 + 2(1-\alpha_2)C_2 - pqb_2^2 - 2\eta_2 V_2\right]}{(\lambda M + \rho_1 V_2 - \rho_2 V_1)^2}$, $\frac{\partial S_2}{\partial \lambda}$ is an increasing function of λ; that is, with the increase in λ, the probability of the system evolving in $Q_1(0, 0)$ direction increases. Similarly, when $\frac{\partial S_2}{\partial \lambda}$ is a decreasing function of λ, the probability of the system evolving in $Q_4(1, 1)$ direction increases with the increase in λ. □

**Proposition 2.** *The stronger the absorptive capacity of spillover technology, the more likely the two entities will choose the active collaborative innovation strategy.*

**Proof.** The following can be derived from Equation (10):

$$\begin{cases} \frac{\partial S_2}{\partial \alpha_1} = \frac{-2C_1}{(1-\lambda+\beta)M + \rho_2 V_1 - \rho_1 V_2} < 0 \\ \frac{\partial S_2}{\partial \alpha_2} = \frac{-2C_2}{\lambda M + \rho_1 V_2 - \rho_2 V_1} < 0 \end{cases} \tag{13}$$

Therefore, the area of $S_2$ decreases with the increase in $\alpha_i$; that is, the probability of the system evolving in the direction of $Q_4(1, 1)$ increases. When the innovation subjects have strong absorptive ability of spillover technology, the innovation subjects can reduce the trial and error in the innovation process by absorbing the existing technological innovation achievements into the collaborative innovation process. This can reduce the innovation cost, thus prompting the innovation subjects to more likely choose the active collaborative innovation strategy. □

**Proposition 3.** *The greater the probability of negative collaborative innovation being discovered, the more likely the two entities choose the active collaborative innovation strategy.*

**Proof.** The following can be derived from Equation (10):

$$\frac{\partial S_2}{\partial p} = \frac{-qb_2^2}{\lambda M + \rho_1 V_2 - \rho_2 V_1} + \frac{-qb_1^2}{(1-\lambda+\beta)M + \rho_2 V_1 - \rho_1 V_2} < 0 \tag{14}$$

Therefore, $\frac{\partial S_2}{\partial p}$ is a monotone decreasing function of p. The area of $S_2$ decreases with the increase in p; that is, it is more likely that the system will evolve in the direction of $Q_4(1, 1)$. When innovation subjects choose negative collaborative behavior, it will not only cause losses to the present interests but will also have negative impact on the future interests. That is to say, the greater the potential loss of reputation caused by negative behavior, the more likely it will be that those subjects will tend to choose active collaborative innovation strategies to maximize their own interests. □

**Proposition 4.** *The greater the reputation discount coefficient, the more likely the two entities choose the active collaborative innovation strategy.*

**Proof.** The following can be derived from Equation (10):

$$\frac{\partial S_2}{\partial q} = \frac{-pb_2^2}{\lambda M + \rho_1 V_2 - \rho_2 V_1} + \frac{-pb_1^2}{(1-\lambda+\beta)M + \rho_2 V_1 - \rho_1 V_2} < 0 \tag{15}$$

According to $\frac{\partial S_2}{\partial q} < 0$, $S_2$ is a monotone decreasing function of q. The area of $S_2$ decreases with the increase in q; that is, it is more likely that the system will evolve in the direction of $Q_4(1, 1)$. When the reputation discount coefficient increases, that is, when the reputation benefit lost by the innovation subjects due to the negative collaborative innovation strategy increases, the probability of the innovation subjects choosing active collaborative innovation strategy increases. □

**Proposition 5.** *The lower the innovation cost, the more likely the two entities will choose the active collaborative innovation strategy.*

**Proof.** The following can be derived from Equation (10):

$$\begin{cases} \frac{\partial S_2}{\partial C_1} = \frac{2(1-\alpha_1)}{(1-\lambda+\beta)M+\rho_2 V_1-\rho_1 V_2} > 0 \\ \frac{\partial S_2}{\partial C_2} = \frac{2(1-\alpha_2)}{\lambda M+\rho_1 V_2-\rho_2 V_1} > 0 \end{cases} \tag{16}$$

According to the Equation (16), $S_2$ is the increment function of $C_i$ (i = 1, 2); that is, with an increase in innovation cost, the area of $S_2$ will increase accordingly. Inversely, when the innovation cost decreases, the area of $S_2$ will decrease, and the probability of the system evolving towards point $Q_4(1, 1)$ will increase. In the process of innovation, based on the bounded rationality, the innovation subjects take the maximization of their own interests as the innovation goal. When the innovation cost is reduced, the innovation subjects can obtain more benefits. Thus, the innovation subjects will be more inclined to choose active collaborative innovation. □

## 5. Numerical Simulation

### *5.1. Parameter Assignment of Related Variables*

Section 4 describes the influence of many factors on the choice of decision-making behavior of general contractors and subcontractors from the perspective of theoretical analysis. Based on the above analysis, using MATLAB 2018a software to simulate the dynamic evolution process of strategy selection, we can depict the impact of initial probability and related factors more intuitively. This paper assumes that at the initial stage, the attitude of the two entities is neutral; that is, the negative level $b_i$ (i = 1,2) of both parties remains at 0.5. To make the numerical simulation more applicable and enhance its guidance, this paper refers to previous research [15,55,56] for parameter assignment, as shown in Table 4. The assignment of each parameter only represents the relative size between each parameter.

Because the basic income has no influence on the subsequent analysis, this paper assigns the basic income of zero.

**Table 4.** Parameter assignment of related variables.

| **Parameter** | $R_1$ | $R_2$ | M | $\eta_1$ | $\eta_2$ | $V_1$ | $V_2$ | $\lambda$ | $\beta$ | $C_1$ |
|---|---|---|---|---|---|---|---|---|---|---|
| Data | 0 | 0 | 6.5 | 0.5 | 0.6 | 4 | 6 | 0.45 | 0.5 | 6 |
| **Parameter** | $C_2$ | $\alpha_1$ | $\alpha_2$ | $\rho_1$ | $\rho_2$ | $b_1$ | $b_2$ | p | q | |
| Data | 5 | 0.6 | 0.5 | 0.6 | 0.5 | 0.6 | 0.5 | 0.6 | 0.7 | |

### *5.2. Influence of Initial Probability on System Evolution Process*

To investigate the influence of the initial probability on the system evolution process, six groups of data were randomly selected for numerical simulation. The evolution processes are shown in Figure 2. From Figure 2, when the initial probabilities of general contractors and subcontractors take different initial values, the final evolution tends towards different selection. There are two stability strategies, (0, 0) and (1, 1), namely {negative collaborative innovation, negative collaborative innovation} and {active collaborative innovation, active collaborative innovation}.

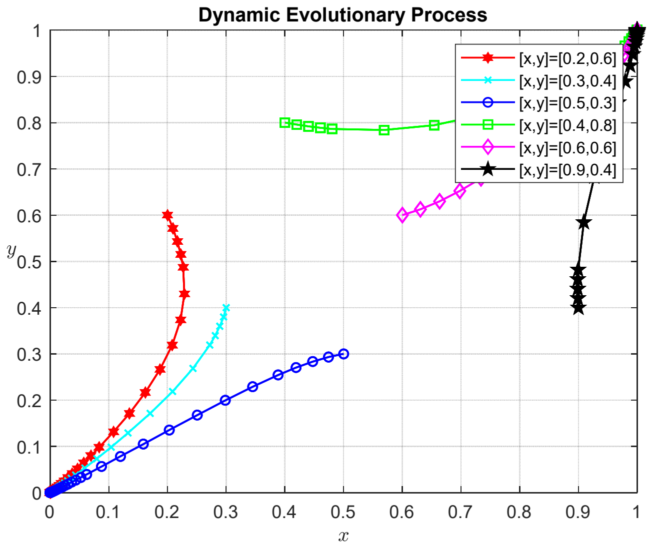


**Figure 2.** Influence of initial probability on system evolution process.

In the process of collaborative innovation, the relationship between two entities is based on the maximization of their own interests. When one entity chooses negative collaborative innovation strategy, there will be "free rider" behavior. The entity can obtain some of the benefits from the active entity without reciprocal benefits flowing to the active entity. At this time, the active entity will cause a change in strategy choice, that is, from active collaborative innovation to negative collaborative innovation. However, when both entities tend to choose the active collaborative innovation strategy, the interests of both entities are maximized. Thus, they will not change the existing strategies.

### *5.3. The Influence of $\lambda$ on the Evolution Results of Both Entities*

From the previous deduction, it can be concluded that there is a specific threshold for the income distribution ratio of collaborative innovation. To find this threshold, this section takes initial state x = 0.5 and y = 0.5 and keeps other parameters unchanged. Let $\lambda$ = 0.35, 0.45, and 0.55, and the influence of $\lambda$ can be obtained, as shown in Figure 3.

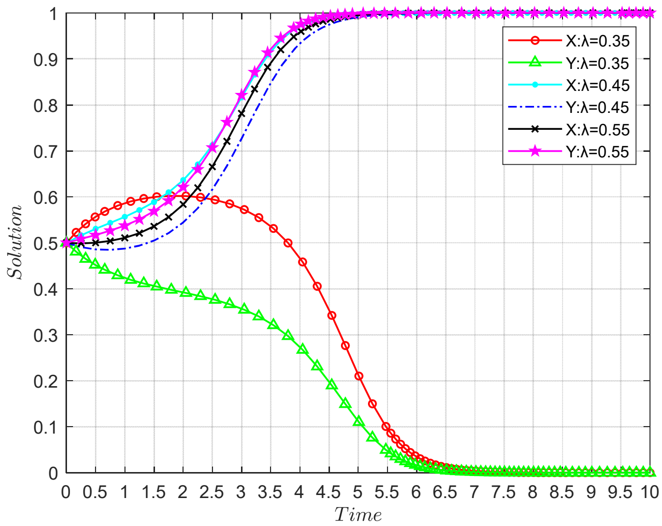


**Figure 3.** The influence of λ on the evolution results of both entities.

It can be concluded that there is a threshold between 0.35 and 0.45, and the numerical simulation results verify the correctness of Proposition 1. When the income distribution ratio is less than the threshold, the system evolves towards negative collaborative innovation. However, when it is greater than the threshold, it will evolve towards active collaborative innovation. This is because, when the ratio is larger, the subcontractors can obtain more innovation benefits, thus increasing the profit level. In this case, subcontractors will choose an active cooperative innovation strategy to gain more benefits. At the same time, since the innovation results are owned by the general contractors, the subcontractors' choice of active cooperative innovation will further promote the output of the innovation results, and under the influence of the subcontractors' strategy, the general contractors will also choose the same strategy. On the contrary, when the ratio is small, the subcontractors will gain more from "free-riding" behavior than from active cooperative innovation. Sensing this situation, the prime contractor will also change its strategy and choose negative cooperative innovation.

### 5.4. The Influence of $\alpha_i$ ($i$ = 1, 2) on the Evolution Results of Both Entities

Based on above analysis, it can be concluded that the influence mechanisms of $\alpha_1$ and $\alpha_2$ are basically the same, so they can be analyzed together. We also take initial state x = 0.5 and y = 0.5, keeping the other parameters unchanged. Because no entities can absorb existing knowledge and technology completely, this paper selects $\alpha_1$ as 0.4, 0.5, and 0.6 and $\alpha_2$ as 0.3, 0.5, and 0.7. The system evolution tracks are shown in Figures 4 and 5.

By comparing the results in Figures 4 and 5, it can be found that there are differences between the both entities in the threshold of spillover technology absorption capacity coefficient. When $\alpha_1$ is between 0.5 and 0.6 and $\alpha_2$ is between 0.3 and 0.5, both general contractors and subcontractors change from negative strategies to active strategies. Therefore, it can be concluded that the spillover technology absorption capacity has different influences on different game players, and the game players will not change the existing innovation strategies when the cost reduction is small.

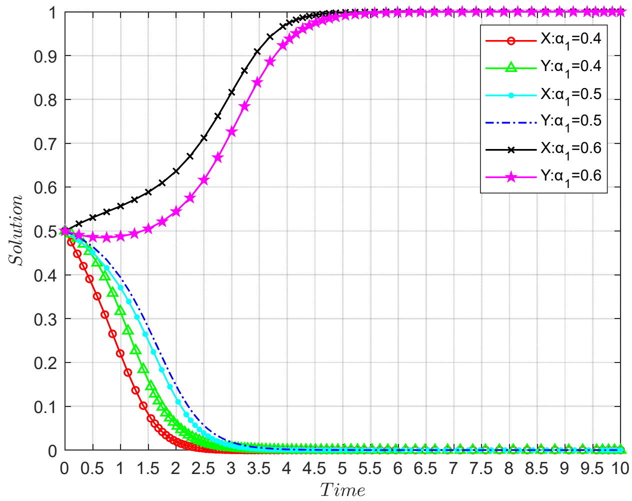


**Figure 4.** The influence of $\alpha_1$ on the evolution results of both entities.

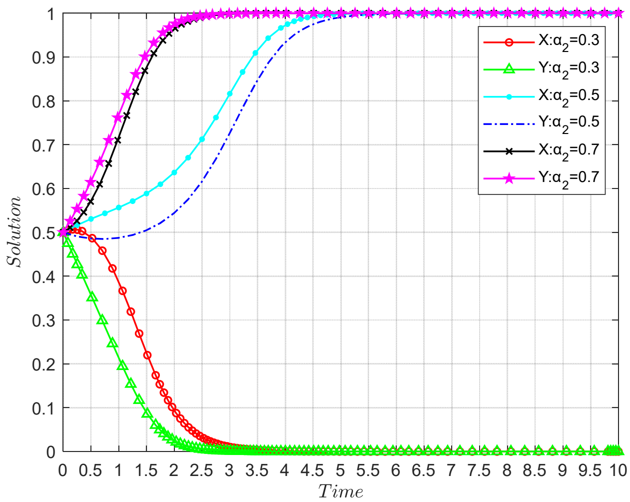


**Figure 5.** The influence of $\alpha_2$ on the evolution results of both entities.

### *5.5. The Influence of p on Evolution Results of Both Entities*

Major projects have extensive and high social attention. Negative behavior will not only bring negative impacts on project quality and progress but also weaken the reputation of construction participants and affect the development of construction participants. In the same way, we take initial state x = 0.5 and y = 0.5 and p = 0.1, 0.3, and 0.5. The influence of p can be obtained, as shown in Figure 6.

It can be seen from Figure 6 that the probability of active collaborative innovation will increase with the increase of p. When p is less than 0.3, that is, when the outside world gives less supervision to the participants in major projects' constructions, the participants will tend to choose negative cooperative behavior. At this point, the opportunistic motivation is strong, and the probability of collaborative innovation gradually tends to zero. However, when external supervision is strong, the risk is higher when the general contractors or subcontractors chooses negative strategies, and once discovered, it will directly affect its reputation, which not only affects its future development but also reduces its profit level. In this case, general contractors and subcontractors will choose active strategies. Therefore, it is necessary to implement appropriate supervision on the construction process to promote the development of technology innovation.

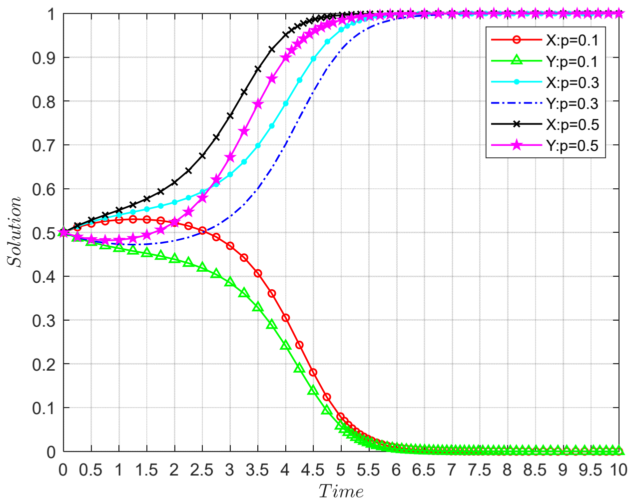


**Figure 6.** The influence of p on the evolution results of both entities.

### *5.6. The Influence of q on Evolution Results of Both Entities*

According to the above analysis, the larger the reputation discount coefficient, the greater the probability that the game players choose active collaborative innovation. Similarly, this section assumes that the reputation discount coefficients are 0.3, 0.4, and 0.5, respectively, and investigates the evolution process under different reputation influence degrees. The simulation results are shown in Figure 7.

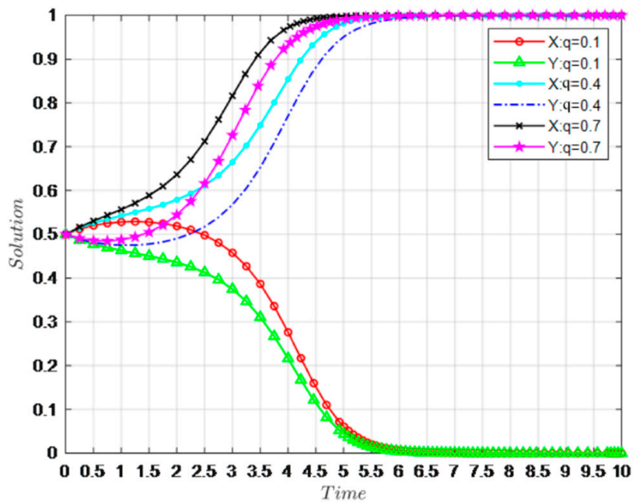


**Figure 7.** The influence of q on the evolution results of both entities.

It can be seen from Figure 7 that the greater the reputation discount coefficient, the more likely it will be that the two entities choose active collaborative innovation strategy. And it also verifies the correctness of Proposition 4. Major projects have social influence beyond general projects. Enterprises participating in major projects' technology innovation and becoming the main subjects of their core technology innovation will significantly enhance their brand value and market influence. Once the negative cooperative behavior is detected, there will be damage to its market reputation and reduced market share, which probably will produce a negative impact on its future development. When the game players realize that the reputation loss caused by negative behavior is too large, to improve influence in the industry and realize the sustainable development strategy, they will have greater enthusiasm for cooperative innovation.

### 5.7. The Influence of $C_i$ ($i$ = 1,2) on the Evolution Results of Both Entities

Different from general projects, major projects have the characteristics of a long investment cycle, complex technology, and large investment in R&D and innovation, which undoubtedly increases the cost and difficulty of innovation. To explore the impact of innovation cost on the decision-making behavior of general contractors and subcontractors, let $C_1$ = 6, 8, and 10 and $C_2$ = 3, 5, and 7, and the influence of $C_i$ (i = 1, 2) can be obtained, as shown in Figures 8 and 9.

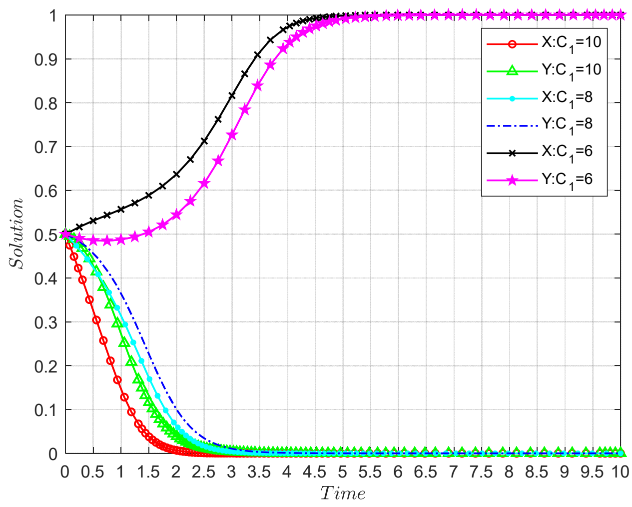


**Figure 8.** The influence of $C_1$ on the evolution results of both entities.

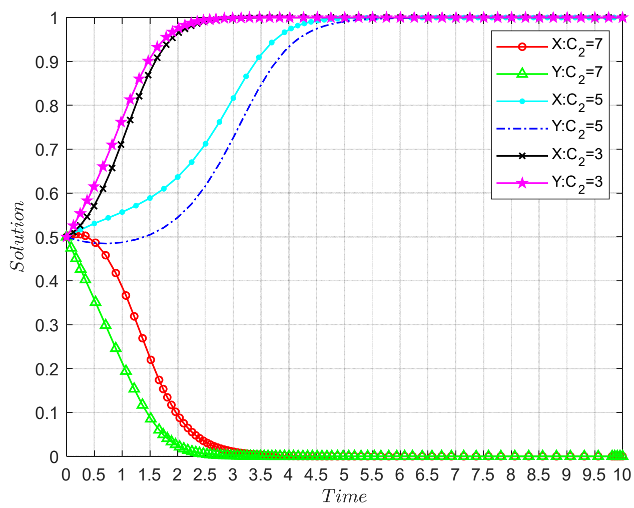


**Figure 9.** The influence of $C_2$ on the evolution results of both entities.

The simulation results show that the lower the innovation cost, the more likely it is that they will choose active collaborative innovation. And this result also verifies Proposition 5. When the innovation cost is too high, it will lead to the cost pressure on them becoming greater under the same income regime. At the same time, due to the significant externality characteristics of technology innovation in major projects, general contractors and subcontractors face greater innovation risks. Therefore, when the innovation cost increases, and the innovation risk is large, the general contractors and subcontractors will choose the negative collaborative innovation strategy. Conversely, when the cost of innovation is small, the general contractors and subcontractors can achieve a higher level of revenue in the process of technology innovation. At the same time, they are more inclined to choose active collaborative innovation strategy due to the reputation effect.

## 6. Conclusions and Managerial Implications

### *6.1. Main Conclusions*

This paper constructs an evolutionary game model of major projects' technology innovation subjects (general contractors and subcontractors), and analyzes the influence factors (e.g., distribution ratio of collaborative innovation benefit, spillover technology absorption capacity coefficient, and reputation discounting coefficient) on the strategy choice. Through numerical simulation, the effect of initial state and related factors is described more intuitively. The research conclusions are as follows:

(1) The evolutionary strategies of general contractors and subcontractors are influenced by the initial probabilities, i.e., the magnitude and difference of the initial probabilities affect their strategy choices. The studies of Qian et al. [15] and Wang et al. [57] have confirmed the idea;

(2) There is a specific threshold for the income distribution ratio of collaborative innovation cooperation between general contractors and subcontractors. If the income distribution ratio favors subcontractors, it is more favorable for them to move in the direction of active collaborative innovation. Conversely, when the income distribution ratio favors general contractors, they end up opting for negative collaborative innovation. Such the conclusion can be found in the studies of Xu et al. [58] and Zhang et al. [59];

(3) Reduced innovation costs positively contribute to the selection of active collaborative innovation decisions by general contractors and subcontractors. Because major projects have long investment cycles, the higher innovation costs will make the innovation subjects bear huge cost pressure and risk, which will affect the decision making. This conclusion is generally recognized by scholars [60];

(4) The spillover technology absorption capacity coefficient, probability of being discovered, and reputation discount coefficient have a positive effect on the strategy selection. Specifically, the larger the above coefficients are, the more the general contractors and subcontractors are inclined to choose an active collaborative innovation strategy. Some of the conclusions can be found in related studies, but this paper draws conclusions contrary to the research of Kong et al. [61].

### *6.2. Managerial Implications*

To improve the willingness to cooperate in major projects' technology innovation, and promote breakthroughs in core technologies, some managerial implications from the government, innovation subjects, and public are put forward:

(1) Relevant government departments can balance the problem of unfair income distribution through financial subsidies and tax incentives. It has been widely confirmed that income distribution is a key factor affecting cooperative relationships [62]. Scholars have found that Shapley can effectively mitigate conflicts of interest arising from income distribution problems [63]. However, this solution does not seem to be based on China's development realities. Major projects are a sign of economic development, which not only enhances China's comprehensive national power and international status but also accelerates the modernization process. The behavior of the innovation subjects in the construction of major projects has a significant impact on the quality and duration of the project, so it is necessary to distribute the income reasonably. Based on China's national conditions, a variety of distribution systems can be explored in terms of inputs of innovation costs, outputs of innovation results, and incentives for cooperation. Coexistence of multiple allocation modalities will effectively mitigate allocation problems;

(2) Factors such as social reputation, level of innovation capacity, and level of innovation resources should be considered when selecting partners. The right choice of partners is a key step in realizing technology innovation and a prerequisite for achieving win-win cooperation [64]. Xie et al. [65] found that public reputation and social reputation were the most common influences when considering partners. Vaez-Alaei et al. [66] found

that the collaborators with more similarity along different dimensions, such as culture, learning ability, geographic distance, and threat, are more likely to cooperate with each other. The innovation ability of participants will directly affect the promotion of major projects' technology innovation process. Therefore, in the process of major engineering and technological innovation, it is important to consider social reputation, level of innovation capacity, and level of innovation resources;

(3) We propose to increase public participation in major projects' innovations. Major projects not only play an important role in the development of national economy but also have a far-reaching impact on the public. For example, the completion of the Three Gorges Dam project not only solved the flood problem in the upper reaches of the Yangtze River but also effectively alleviated the shortage of electricity in our society. Improving public participation can not only make the public perceive the social benefits brought by the construction of major projects, but to a certain extent, they can also play a supervisory role on the participants in major projects and technological innovation.

### *6.3. Limitations and Future Research Directions*

There are several limitations in our works. We constructed the evolutionary game model to analyze the dynamic change of decision-making behaviors between general contractors and subcontractors and explore how the key factors influence each entity selecting active strategies. However, this paper is from the theoretical point of view and lacks engineering construction and technological innovation data, so there will be differences between the research conclusions and actual major projects. In addition, this paper selects only a few of the major projects' technology innovation influencing factors for research. Future research could incorporate more influences into the model.

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**Data Availability Statement:** The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

**Conflicts of Interest:** The authors declare no conflict of interest.

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