

Article

Trilateral Evolutionary Game Strategy for the Design Optimization of Engineering General Contracting Projects in the Chinese Context

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Abstract: The engineering general contracting mode is an advanced engineering transaction mode, and design optimization is one of the important driving forces for vigorously promoting the general contracting mode. The application proportion of the general contracting mode in infrastructure projects is not high, the number of successful projects is not large, and the implementation effect is not ideal. One of the main reasons is that the design optimization theory and practice of international standard general contracting projects cannot adapt to the general contracting projects in the Chinese context, making local general contracting projects face huge challenges such as low enthusiasm for design optimization from all parties and unsatisfactory design optimization effects. Therefore, under the premise of bounded rationality, when the owner adopts control methods of different intensities, an evolutionary game study on the selection of design optimization strategies between the design and construction parties is carried out, and stability control strategies are proposed through case experiments and simulations. The research results indicate the following: firstly, the design optimization of general contracting projects in the Chinese context is feasible, but it depends on the distribution ratio of benefits obtained from the design optimization. Compared with general civil construction general contracting projects, the design optimization allocation ratio of industrial construction general contracting projects is more significant; secondly, the mixed control method of strong control and weak control is the optimal choice for the owner of the general contracting project; and thirdly, there are multiple evolutionary stable points, and mechanism design or incentive measures should be used to guide owners to choose weak control strategies, while design and construction parties should choose their design optimization strategies. The research results provide a reference for owners to determine the proportion and scheme of design optimization allocation, and for construction parties to determine design optimization strategies.



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1. Introduction

The general contracting mode is an advanced engineering transaction mode (organizational management mode) that can achieve deep integration between engineering project design, procurement, and construction, effectively overcoming the adverse effects of DBB mode on engineering goals, and thus achieving the goal of increasing the value of engineering project construction [1]. The general contracting mode is the key to solving some prominent problems in the current engineering construction field, such as internal consumption, ineffective work, industrial chain fragmentation, and weak enterprises. It has attracted close attention from construction administrative authorities at all levels, owners, and other general contracting markets. Through theoretical research and engineering



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practice, the management level of China's engineering general contracting projects (referred to as general contracting projects) has been improved to a certain extent, and certain experience and phased achievements have been achieved. However, as a whole, the scale of China's engineering general contracting construction market (referred to as the general contracting market) is still very small. Jiangsu Province is a large national construction province, and also a province where the general contracting mode is relatively well carried out, and the proportion of its general contracting mode application is representative. Taking the general contracting project of the construction industry in Jiangsu Province as an example, the statistical data of Jiangsu Provincial Department of Housing and Construction show that the proportion of the engineering general contracting mode in 2020 was 3.6% and the proportion of the engineering general contracting mode in 2021 was 4%. The situation in 2023 was the same as that in 2020 and 2021, and the proportion of the number of contracts in engineering general contracting mode was not more than 10%, which is much lower than the 30–50% scale of the international general contracting market. Design optimization is the main driving force for promoting and applying the general contracting mode but due to factors such as the special management system of China's engineering construction projects, the developmental stage of the general contracting market environment, the characteristics of general contracting projects, and insufficient understanding and understanding in the industry, the mature theory and practical experience of design optimization under the international standard general contracting mode cannot adapt to the general contracting mode in the Chinese context. As a result, the design optimization of general contracting projects faces huge challenges, such as low enthusiasm for design optimization by the general contractors and unsatisfactory design optimization results. It can be seen that how to conduct research on the tripartite evolutionary game of design optimization for general contracting projects in the Chinese context, and propose corresponding stability strategies, to effectively stimulate the enthusiasm of all parties in the general contracting market to carry out design optimization and promote the application of the general contracting mode, is an urgent problem that needs to be solved. Therefore, based on the issues studied in this paper, the engineering general contracting project management theory is adopted to analyze the industrial value chain, enterprise value chain, and construction product value chain, as well as the value-added forms and contents of the general contracting project. Incentive theory is used to analyze the incentive mechanism of the engineering general contracting consortium and the essence of consortium design optimization.

Information asymmetry is one of the reasons for a series of problems in construction project management [2,3]. Based on this premise, the scholars have conducted a series of studies. Shen W and Asce S M et al. [4] studied the cooperative interface problem caused by information asymmetry, analyzed in detail the role of formal contracts and social norms in interface management, and proposed renovation suggestions. Wang Dedong and Fang Shaoze [5] claimed that information asymmetry under the EPC mode makes it easy for the general contractor to adopt opportunistic behavior, which can cause losses to the owner. They further proposed that the cost of opportunism should be increased to effectively suppress the opportunistic tendency and level of opportunistic behavior of the general contractor. Zhang Hong and Shi Yike [6] shared the same view, believing that the problem of information asymmetry between owners and contractors is more pronounced under the EPC mode, and the characteristics of the "principal-agent" model are more obvious. Therefore, they studied how to reduce the opportunistic behavior of contractors in this situation and have never better motivated them to improve their efforts. Liu XZ et al. [7] explored the incentive contract issue of EPC projects under information asymmetry based on the principal-agent theory and incentive mechanisms. Many scholars have used models to analyze the game relationships between different entities in EPC projects. Cao, GM et al. [8] analyzed that credit accumulation and long-term benefits will affect the decisions of the general contractor and subcontractors in repeated games, ultimately achieving a "win-win situation" of Pareto benefits and stable cooperative relationships. Wang, SW et al. [9] established a tripartite evolutionary game model of government owner

construction enterprise and analyzed the impact of stakeholder behavior and strategic choices on the stable development of EPC mode. Pan Yumin et al. [10] studied the principal–agent risk in EPC projects based on evolutionary game theory and believed that the construction of incentive mechanisms can weaken the impact of risk. Jiang, WP et al. [11] investigated the formation of cooperation mechanisms among EPC project consortia in the Chinese scenario from a trusted perspective and concluded that reputation and communication are the key influencing factors. Yang et al. [12] analyzed the risk issues in international EPC projects from the perspective of evolutionary game theory and believed that contractors can improve project performance by applying partnership relationships. Ding JY et al. [13] explored the key factors affecting the sharing of value-added benefits in large-scale EPC hydropower projects, providing theoretical guidance for design optimization and incentive mechanisms for EPC projects. Liu Renhui and Cong Xiaolin [14] utilized the EPC project as their research object, with the objective function of maximizing the utility of the owner, the participation constraint of the minimum income of the general contractor being greater than the opportunity cost, and the incentive constraint of the marginal income of the general contractor being equal to the marginal cost, put forward a principal–agent model to analyze the relationship between agency costs and various asymmetric factors and utilized corresponding measures to reduce agency costs and improve owner benefits. Zhang Hui et al. [15] introduced relational contracts into incentive mechanisms and demonstrated through numerical analysis that this incentive mechanism can improve EPC project performance. By introducing the theory of fairness concerns, Lv Junna [16] and An Xiaowei [17], respectively, studied the distribution of benefits between the general contractor and subcontractors, as well as between the two parties of the consortium, and obtained the optimal effort level and optimal benefit distribution ratio of the research objects in an equilibrium state. Zhu Jianbo et al. explored the impact of fair preference theory on the distribution coefficient of benefits and the acceptance rate of design changes in the cooperation process between design and construction parties.

The introduction of information technology provides new ideas for solving information asymmetry in EPC modes [18]. Lee CY and Chong HY [19,20] developed the application of Building Information Modeling (BIM) in EPC projects. They analyzed the synergistic and fusion effects of BIM, positing that the application of information technology can reduce information asymmetry and substantially enhance the performance of EPC projects [21]. Zhang Shirong [22] and Sun, CS [23], and others have conducted similar research. In addition, compared with the traditional DBB mode, the EPC mode also faces some new problems. Shen Zhifeng and Wang Peng et al. [24] studied the inadequacy of the traditional engineering quality supervision system under the EPC mode and, based on the construction of a grounded theory, studied the supervision system of EPC projects. They proposed measures such as simplifying the EPC project approval process, leveraging the role of engineering insurance mechanisms, and strengthening the construction of integrity systems. Zhang Qingzhen and Tang Wenzhe [25] believed that in the composition system of contractors in China, construction companies have good technical advantages, but their design capabilities are insufficient. They proposed to choose appropriate design parties as partners to enhance their design capabilities. Tang Wenzhe [26] and Wang Tengfei [27] conducted extensive research in design management and constructed a single to multiple incentive model between the general contractor and the design party, proposing design incentive strategies. Hu WF et al. [28] established a multi-level incentive model for the multi-level management system formed by owners, contractors, and subcontractors and explored the issue of multi-party benefit distribution. On this basis, Zhao Chenyuan et al. [29] proposed a chain-based multiple principal–agent incentive model considering the scenario where some agents in the principal–agent relationship are both principals and agents. In promoting the design optimization of EPC projects, Shi ZY [30] analyzed the conditions and influencing factors for optimizing the design of EPC general contracting projects and provided solutions. Zhao Yue and Qiang Maoshan [31], based on the characteristics of the

EPC mode, studied the impact of the depth of the owner's preliminary bidding design documents on the owner's bidding design strategy with the changes in the cost–benefit ratio of optimized design and the owner's risk-taking ratio. They believed that projects with unclear outputs should adopt a deep design strategy, while projects that only focus on output functions can adopt a shallow design strategy. Chen Y [32] believed that design optimization can achieve the sustainable development of EPC projects and analyzed the factors that affect design optimization.

Based on the above research results, relevant scholars have conducted much research on the practice of the general contracting mode, exploring and researching the application of BIM technology, designing incentives, and strengthening cooperation between both parties. However, there has been no research on the design optimization of general contracting projects in the Chinese context. This article is based on the current practical situation of design optimization for general contracting projects, analyzes the background of proposing design optimization problems for general contracting projects in the Chinese context, researches the tripartite evolutionary game of design optimization for general contracting projects, and proposes stability control strategies.

In the realm of engineering practices in China, there are, in fact, two primary types of consortium that dominate the scene—one is helmed by the design party, while the other is led by the construction party. Considering the author's practical experience and case characteristics, this paper chooses the consortium with the construction party as the analysis object.

Moreover, the main contributions of this paper are summarized as follows:

1. In response to the relatively balanced risk sharing and strict control approach in the Chinese context, a general contracting project design optimization evolutionary game model has been constructed, which overcomes the shortcomings of international standard general contracting project design optimization theory and practice that cannot adapt to China's conditions and compensates for China's general contracting project design optimization theory;
2. Taking China's general contracting consortium, which is the main form, as the research object, this paper analyzes the game stability of the three-party evolution in the design optimization of the general contracting project, proposes their stability strategies, and provides strategies for all parties to carry out design optimization;
3. A hybrid control method has been proposed, which not only adapts to the current general contracting project management system but also makes design optimization feasible.

The rest of the paper is organized as follows. Section 2 elaborates on the related work. In Section 3, the proposed model is structured using the evolutionary game theory. In Section 4, the stability analysis of the tripartite evolutionary game model is structured. In Section 5, the case study is conducted and discussed. Finally, the conclusion and future research directions are discussed in Section 6.

2. Relate Work

2.1. Current Situation of Design Optimization and Analysis of Chinese Context

Firstly, we analyze the mechanism of optimizing the design of international standard general contracting projects, and secondly, we analyze the Chinese context under the general contracting mode.

The design optimization of international standard general contracting projects [32] is shown in Figure 1.

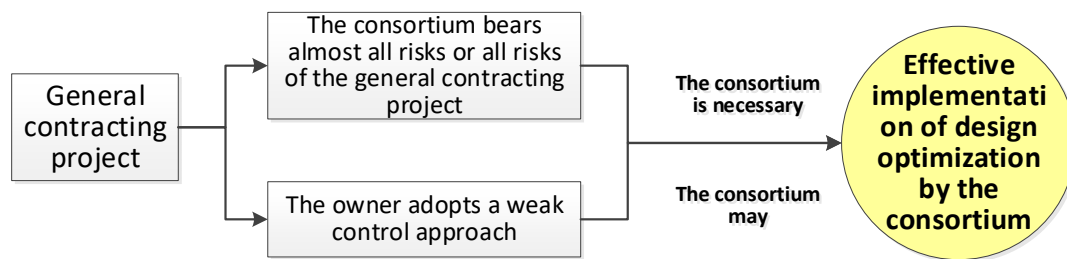


Figure 1. Design optimization of international standard general contracting project consortium.

According to Figure 1, on the one hand, the international standard general contracting project consortium must bear almost all or all risks of the project, which objectively forces the consortium to seek effective methods to mitigate risks. Design optimization is the main method for the consortium to effectively mitigate risks. On the other hand, the international standard general contracting project owner adopts a weak control approach, which makes it possible and provides space for the consortium to carry out design optimization, making it possible to effectively resolve risks through design optimization. It can be seen that the international standard general contracting mode has formed an effective mechanism for design optimization through contracts.

Compared with the current state of design optimization for international standard general contracting projects, the design optimization of China's general contracting projects is completely different, which is shown in Figure 2.

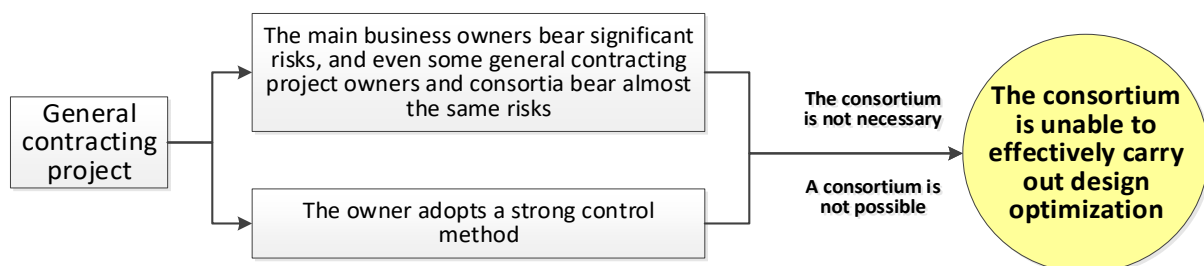


Figure 2. Current status of design optimization for China's general contracting project consortia.

According to Figure 2, on the one hand, China's general contracting project industry mainly bears significant risks, leading to a lack of necessity for the consortium to carry out design optimization as well as a lack of enthusiasm for design optimization by the consortium. On the other hand, China's general contracting project owners adopt a strong control approach, which makes it impossible or insufficient for the consortium to carry out design optimization, making it impossible to effectively mitigate risks through design optimization. It can be seen that China's general contracting project consortium has neither enthusiasm nor the possibility of design optimization, which is opposite to the design optimization of international standard general contracting projects.

Based on the above analysis, it can be concluded that the Chinese context related to design optimization in the general contracting mode hinders the development of joint venture design optimization work.

(1) The risk sharing between China's general contracting project owners and consortia is relatively balanced. The international standard general contracting project consortium must bear almost all risks or bear all risks, which means that the owner hardly needs to bear risks. Relatively speaking, China's general contracting project owners have to bear more risks, which means that the degree of consortium is relatively small. The result is that the international standard general contracting consortium subjectively has the motivation to carry out design optimization, while China's general contracting consortium does not have the motivation in terms of design optimization.

(2) China's general contracting project owners adopt a strong control approach. The international standard general contracting project owner adopts a weak control approach, which means that the owner does not need to strictly control the design scheme, construction organization design scheme, process, material, equipment quality, etc., of the consortium. In this case, the consortium has sufficient space to carry out design optimization. Relatively speaking, China's general contracting project owners adopt a strong control approach, which means that the owners strictly control the design scheme, construction organization design scheme, process, material, equipment quality, etc., of the consortium, which means that the consortium does not have sufficient control to carry out design optimization. The result is that the international standard general contracting consortium has enough space to carry out design optimization, while China's general contracting consortium does not have enough space to carry out design optimization.

In summary, in the aforementioned Chinese context, conducting a tripartite game and countermeasure study on the design optimization of the general contracting projects can maximize the enthusiasm of the consortium to actively carry out design optimization work.

2.2. The Proposal of Problems

Research Question: For a general contracting project consortium led by the construction party, how can the owner determine the distribution ratio of design optimization benefits to motivate the construction party and the design party to adopt design optimization strategies and carry out design optimization work? The specific issues are as follows:

1. How can we motivate the general contracting project consortium to carry out design optimization in the context of relatively small risks?
2. How can we provide sufficient space for the consortium to carry out design optimization in the context of strong control measures adopted by the general contracting project owner?

Innovation Points: (1) In response to the Chinese context of relatively balanced risk sharing and strict control methods, an evolutionary game model for the design optimization of the general contracting projects has been constructed, which overcomes the shortcomings of international standard general contracting project design optimization theory and practice that cannot adapt to China's conditions and makes up for China's general contracting project design optimization theory; (2) Taking China's general contracting consortium, which is the main form, as the research object, this paper analyzes the game stability of the three-party evolution of design optimization for the general contracting projects, proposes their own stability strategies, and provides strategies for all parties to carry out design optimization; (3) A hybrid control method has been proposed, which not only adapts to the current general contracting project management system, but also makes design optimization feasible.

3. The Proposed Model

3.1. Model Assumptions

Assumption 1. The three parties involved in the game are the participants of the general contracting project, namely the owner, the consortium leader (construction enterprise), and the consortium participant (design institute). The three parties have limited rationality and pursue the maximization of their interests [33].

Assumption 2. The designer and constructor can choose whether to perform design optimization in different scenarios. Without considering any extrinsic effects, assuming that the probability that the designer chooses the optimization strategy is x , the probability that the designer chooses the non-optimization strategy is $1 - x$; the probability of (the constructor) choosing the optimization strategy is y , and the probability of choosing the non-optimization strategy is $1 - y$.

Assumption 3. The owner is the owner of the general contracting project, and the pursuit of maximizing the comprehensive benefits of the project is the core goal. Therefore, in any situation, the owner will encourage the consortium to carry out design optimization. To encourage the bidding

consortium to carry out design optimization, the owner allocates the benefits generated by the design optimization among the three parties, and the distribution ratios obtained by the owner, the constructor, and the designer are γ_1 , γ_2 , and γ_3 . There is $0 \leq \gamma \leq 1$, and $\gamma_1 + \gamma_2 + \gamma_3 = 1$.

Assumption 4. Both scheme design optimization and engineering design optimization are based on the mature scheme (low degree of risk) to adjust, which will increase the risk of project implementation. The risk will be distributed among the three parties, and the proportions shared by the owner, the constructor, and the designer are λ_1 , λ_2 , and λ_3 . There is $0 \leq \lambda < 1$, and $\lambda_1 + \lambda_2 + \lambda_3 = 1$.

Assumption 5. The owners of different general contracting projects adopt different project control methods. Specifically, the owners can choose strong control and weak control. Assuming that the probability of owners choosing strong control is z , and the probability of owners choosing weak control is $1 - z$. Strong control refers to the owner's deep involvement in project process control, including quality management, schedule management, safety management, investment control, etc. Different intensity of control corresponds to different intensity of investment. When the owner chooses the strong control mode, compared with the weak control mode, the owner will produce a supervision cost C_1 , including the cost of entrusting construction supervisors, entrusting follow-up auditing companies, entrusting quality inspection, etc.

Assumption 6. If the design optimization occurs, the owner and the constructor will obtain the inherent income R_o and R_c (the designer only obtains the inherent income R_d). At the same time, the owner and the constructor will obtain the implicit added-value $\xi_1 R_o$ and $\xi_2 R_c$. The implicit added value mainly comes from the reduction in practice quantity and the reduction in cost caused by the shortening of the construction period. The values of ξ_1 and ξ_2 are generally 0~0.3.

Assumption 7. When the owner chooses strong control, the constructor and the designer will increase additional costs. As the leader of the consortium, the constructor will increase the management cost C_2 , and the influence coefficient is k_2 . Under the strong control mode, the cost of the designer will also increase, and the influence coefficient is k_3 . According to practical engineering management experience, the values of k_2 and k_3 are generally 1.0~1.2.

Assumption 8. When the designer provides the design optimization scheme or optimization suggestion if the constructor decides not to optimize, the project does not carry on the design optimization. The designer produces the design cost and no benefit. When the constructor decides to optimize, the designer adopts a negative attitude to deal with the optimization work or has no professional ability to carry out design optimization, the designer will bear the liquidated damages $C_{\Delta 1}$. The constructor will entrust other designers to carry out specific design optimization, and the additional commission cost is $C_{\Delta 2}$.

3.2. Payoff Matrix

Based on China's engineering practice and the above assumptions and conditions, the payoff matrix [34] of the multi-player game can be obtained in Table 1.

Table 1. Payment matrix of the multi-player game in the general contracting project.

Designer	Contractor	Owner	
		Strong Control (z)	Weak Control ($1 - z$)
Optimization (x)	Optimization (y)	$R_d + \gamma_3 I - k_3 C_3 - \lambda_3 I$ $R_c + \gamma_2 I + \xi_2 R_c - k_2 C_2 - \lambda_2 I$ $R_o + \gamma_1 I + \xi_1 R_o - C_1 - \lambda_1 I$	$R_d + \gamma_3 I - C_3 - \lambda_3 I$ $R_c + \gamma_2 I + \xi_2 R_c - C_2 - \lambda_2 I$ $R_o + \gamma_1 I + \xi_1 R_o - \lambda_1 I$
	Non-optimization ($1 - y$)	$R_d - k_3 C_3$ $R_c - k_2 C_2$ $R_o - C_1$	$R_d - C_3$ $R_c - C_2$ R_o
Non-optimization ($1 - x$)	Optimization (y)	$R_d - C_{\Delta 1}$ $R_c + \gamma_2 I + \xi_2 R_c - k_2 C_2 - \lambda_2 I - C_{\Delta 2}$ $R_o + \gamma_1 I + \xi_1 R_o - C_1 - \lambda_1 I$	$R_d - C_{\Delta 1}$ $R_c + \gamma_2 I + \xi_2 R_c - C_2 - \lambda_2 I - C_{\Delta 2}$ $R_o + \gamma_1 I + \xi_1 R_o - \lambda_1 I$
	Non-optimization ($1 - y$)	R_d $R_c - k_2 C_2$ $R_o - C_1$	R_d $R_c - C_2$ R_o

3.3. Model Construction

The expected returns of the design party adopting optimization and non-optimization strategies are represented by U_{D1} and U_{D2} , respectively, with an average expected return of $\overline{U_D}$. According to the game payment matrix in Table 1, there are the following:

$$\begin{aligned} U_{D1} &= yz(R_d + \gamma_3 I - K_3 C_3 - \lambda_3 I) + y(1-z)(R_d + \gamma_3 I - C_3 - \lambda_3 I) \\ &\quad + z(1-y)(R_d - K_3 C_3) + (1-y)(1-z)(R_d - C_3) \\ U_{D2} &= yz(R_d - C_{\Delta 1}) + y(1-z)(R_d - C_{\Delta 1}) + z(1-y)R_d + (1-y)(1-z)R_d \\ \overline{U_D} &= xU_{D1} + (1-x)U_{D2} \end{aligned} \quad (1)$$

Similarly, the average expected returns of the construction party and the owner are $\overline{U_C}$ and $\overline{U_O}$, respectively.

$$\begin{aligned} U_{C1} &= xz(R_c + \gamma_2 I + \xi_2 R_c - k_2 C_2 - \lambda_2 I) + x(1-z)(R_c + \gamma_2 I + \xi_2 R_c - C_2 - \lambda_2 I) \\ &\quad + (1-x)z(R_c + \gamma_2 I + \xi_2 R_c - k_2 C_2 - \lambda_2 I - C_{\Delta 2}) + (1-x)(1-z)(R_c + \gamma_2 I + \xi_2 R_c - C_2 - \lambda_2 I - C_{\Delta 2}) \\ U_{C2} &= xz(R_c - k_2 C_2) + x(1-z)(R_c - C_2) + (1-x)z(R_c - k_2 C_2) + (1-x)(1-z)(R_c - C_2) \\ \overline{U_C} &= yU_{C1} + (1-y)U_{C2} \end{aligned} \quad (2)$$

$$\begin{aligned} U_{O1} &= xy(R_0 + \gamma_1 I + \xi_1 R_0 - C_1 - \lambda_1 I) + x(1-y)(R_0 - C_1) + (1-x)y(R_0 + \gamma_1 I + \xi_1 R_0 - C_1 - \lambda_1 I) \\ &\quad + (1-x)(1-y)(R_0 - C_1) \\ U_{O2} &= xy(R_0 + \gamma_1 I + \xi_1 R_0 - \lambda_1 I) + x(1-y)R_0 + (1-x)y(R_0 + \gamma_1 I + \xi_1 R_0 - \lambda_1 I) \\ &\quad + (1-x)(1-y)R_0 \\ \overline{U_O} &= zU_{O1} + (1-z)U_{O2} \end{aligned} \quad (3)$$

According to the Malthusian dynamic equation, the rate of change chosen by the designer's strategy, i.e., $F(y)$, can be formulated as follows:

$$\begin{aligned} F(x) &= \frac{dx}{dt} = x(U_{D1} - \overline{U_D}) = x(1-x)(U_{D1} - U_{D2}) \\ &= x(1-x)(y\gamma_3 I - Zk_3 C_3 - y\lambda_3 I - C_3 + ZC_3 + yC_{\Delta 1}) \end{aligned} \quad (4)$$

Similarly, the change rate of the contractor strategy selection and the change rate of the owner strategy selection is $F(z)$:

$$\begin{aligned} F(y) &= \frac{dy}{dt} = y(U_{C1} - \overline{U_C}) = y(1-y)(U_{C1} - U_{C2}) \\ &= y(1-y)(xC_{\Delta 2} - C_{\Delta 2} + \gamma_2 I - \lambda_2 I + \xi_2 R_c) \end{aligned} \quad (5)$$

$$\begin{aligned} F(z) &= \frac{dF(z)}{dt} = z(U_{O1} - \overline{U_O}) = z(1-z)(U_{O1} - U_{O2}) \\ &= z(1-z)(-C_1) \end{aligned} \quad (6)$$

By combining Equations (4)–(6), the dynamic equation system replicated by the design party, construction party, and owner is obtained:

$$\begin{cases} F(x) = x(1-x)(y\gamma_3 I - zk_3 C_3 - y\lambda_3 I - C_3 + zC_3 + yC_{\Delta 1}) \\ F(y) = y(1-y)(xC_{\Delta 2} - C_{\Delta 2} + \gamma_2 I - \lambda_2 I + \xi_2 R_c) \\ F(z) = z(1-z)(-C_1) \end{cases} \quad (7)$$

4. Stability Analysis of Tripartite Evolutionary Game Model

4.1. Evolutionary Stability Analysis of Tripartite Entities

4.1.1. Analysis of Evolutionary Stability of Designers

When $y\gamma_3 I - y\lambda_3 I - zk_3 C_3 + zC_3 - C_3 + yC_{\Delta 1} = 0$, that is, $y = y_0 = \frac{-zk_3 C_3 + zC_3 - C_3}{-\gamma_3 I + \lambda_3 I + C_{\Delta 1}}$, and there is a constant $F(x) = 0$, for any x , this is a stable strategy of the designer.

When $y\gamma_3 I - y\lambda_3 I - zk_3 C_3 + zC_3 - C_3 + yC_{\Delta 1} \neq 0$, according to evolutionary stability theory, if there is a strategy x^* , the designer is in a stable state.

a. If $y\gamma_3I - y\lambda_3I - zk_3C_3 + zC_3 - C_3 + yC_{\Delta 1} > 0$, that is, when $y > y_0 = \frac{-zk_3C_3 + zC_3 - C_3}{-\gamma_3I + \lambda_3I + C_{\Delta 1}}$, there is $\frac{dF(x)}{dx}\bigg|_{x=0} > 0$ and $\frac{dF(x)}{dx}\bigg|_{x=1} < 0$. It can be seen that $x = 1$ (the designer's choice of optimization) is a stable strategy.

b. If $y\gamma_3I - y\lambda_3I - zk_3C_3 + zC_3 - C_3 + yC_{\Delta 1} < 0$, that is, when $y < y_0 = \frac{-zk_3C_3 + zC_3 - C_3}{-\gamma_3I + \lambda_3I + C_{\Delta 1}}$, there is $\frac{dF(x)}{dx}\bigg|_{x=0} < 0$ and $\frac{dF(x)}{dx}\bigg|_{x=1} > 0$. It can be seen that $x = 0$ (the designer's choice of non-optimization) is a stable strategy.

The evolution phase diagram of the designer is shown in Figure 3.

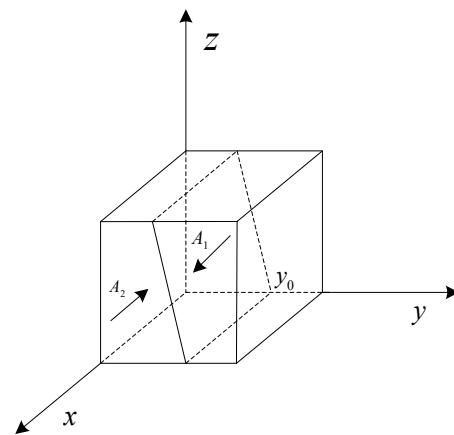


Figure 3. Evolutionary phase diagram of designer. The volumes of regions represent the probabilities of the designer choosing the “optimization” strategy and “non-optimization” strategy.

Marking $\Omega = \{(x, y, z) | 0 \leq x \leq 1, 0 \leq y \leq 1, 0 \leq z \leq 1\}$, it can be seen from Figure 3 that the surface $y = y_0 = \frac{-zk_3C_3 + zC_3 - C_3}{-\gamma_3I + \lambda_3I + C_{\Delta 1}}$ divides Ω into two spaces A_1 and A_2 . When the initial region falls to A_1 ($y > y_0$), the strategy of the designer evolves into optimization. When the initial region falls in A_2 ($y < y_0$), the strategy of the designer evolves into non-optimization.

4.1.2. Analysis of Evolutionary Stability of Construction Parties

When $x C_{\Delta 2} - C_{\Delta 2} + \gamma_2 I - \lambda_2 I + \xi_2 R_c = 0$, that is, $x = x_0 = \frac{C_{\Delta 2} + \lambda_2 I - \gamma_2 I - \xi_2 R_c}{C_{\Delta 2}}$, and there is a constant $F(y) = 0$, for any y , this is a stable strategy of the constructor.

When $x C_{\Delta 2} - C_{\Delta 2} + \gamma_2 I - \lambda_2 I + \xi_2 R_c \neq 0$, it is divided into two cases:

a. If $x C_{\Delta 2} - C_{\Delta 2} + \gamma_2 I - \lambda_2 I + \xi_2 R_c > 0$, that is, $x > x_0 = \frac{C_{\Delta 2} + \lambda_2 I - \gamma_2 I - \xi_2 R_c}{C_{\Delta 2}}$, there is $\frac{dF(y)}{dy}\bigg|_{y=0} > 0$ and $\frac{dF(y)}{dy}\bigg|_{y=1} < 0$. It can be seen that $y = 1$ (the constructor's choice of optimization) is a stable strategy.

b. If $x C_{\Delta 2} - C_{\Delta 2} + \gamma_2 I - \lambda_2 I + \xi_2 R_c < 0$, that is, $x < x_0 = \frac{C_{\Delta 2} + \lambda_2 I - \gamma_2 I - \xi_2 R_c}{C_{\Delta 2}}$, there is $\frac{dF(y)}{dy}\bigg|_{y=0} < 0$ and $\frac{dF(y)}{dy}\bigg|_{y=1} > 0$. It can be seen that $y = 0$ (the constructor's choice of non-optimization) is a stable strategy. The evolutionary phase diagram of the constructor is shown in Figure 4.

Marking $\Omega = \{(x, y, z) | 0 \leq x \leq 1, 0 \leq y \leq 1, 0 \leq z \leq 1\}$, it can be seen from Figure 4 that the surface $x = x_0 = \frac{C_{\Delta 2} + \lambda_2 I - \gamma_2 I - \xi_2 R_c}{C_{\Delta 2}}$ divides Ω into two spaces B_1 and B_2 . When the initial region falls to B_1 ($x > x_0$), the constructor's strategy evolves into optimization. When the initial region falls in B_2 ($x < x_0$), the constructor's strategy evolves into non-optimization.

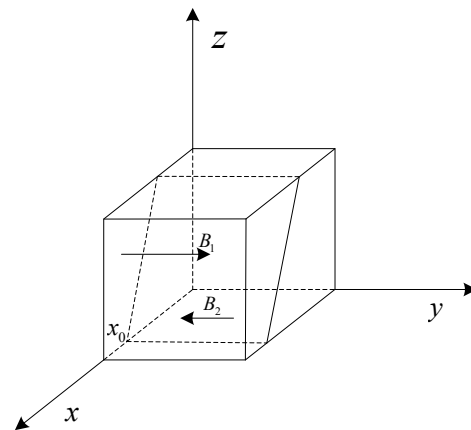


Figure 4. Evolutionary phase diagram of constructor. The volumes of regions B_1 and B_2 represent the probabilities of the constructor choosing the “optimization” strategy and “non-optimization” strategy.

4.1.3. The Stability Analysis of the Owner

Since $-C_1 < 0$ is constant, there is $\frac{dF(z)}{dz}\big|_{z=0} < 0$ and $\frac{dF(z)}{dz}\big|_{z=1} > 0$, and it can be seen that $z = 0$ (owner’s choice of weak control) is a stable strategy.

4.2. System Stability Analysis

When the replication equations are equal to zero, it shows that the speed and direction of the three-party strategy adjustment of the evolutionary game system do not change, so that the system reaches a relatively stable equilibrium state. Therefore, letting $F(x) = 0$, $F(y) = 0$, and $F(z) = 0$ in Formula (7), we can obtain eight Nash equilibrium points of the system, that is, $O(0,0,0)$, $A(0,0,1)$, $B(0,1,0)$, $C(0,1,1)$, $D(1,0,0)$, $E(1,0,1)$, $F(1,1,0)$, and $G(1,1,1)$. According to Lyapunov’s first method, the system can be considered to be stable when all eigenvalues of the system Jacobian matrix are negative real parts.

$$\begin{bmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} & \frac{\partial F(x)}{\partial z} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} & \frac{\partial F(y)}{\partial z} \\ \frac{\partial F(z)}{\partial x} & \frac{\partial F(z)}{\partial y} & \frac{\partial F(z)}{\partial z} \end{bmatrix} = \begin{bmatrix} (1-2x)(y\gamma_3I - y\lambda_3I - Zk_3C_3 + ZC_3 - C_3 + yC_{\Delta 1}) & x(1-x)(\gamma_3I - \lambda_3I + C_{\Delta 1}) & x(1-x)(1-k_3)C_3 \\ yC_{\Delta 2}(1-y) & (1-2y)(xC_{\Delta 2} - C_{\Delta 2} + \gamma_2I - \lambda_2I + \xi_2R_c) & 0 \\ 0 & 0 & C_1(2z-1) \end{bmatrix} \quad (8)$$

Each equilibrium point is substituted into the above Jacobian matrix to obtain the corresponding eigenvalues (as shown in Table 2), and then the stability of each equilibrium point is judged as shown in Table 3.

Table 2. Eigenvalues of the Jacobian matrix.

Equilibrium Point	Characteristic Value 1	Characteristic Value 2	Characteristic Value 3
$O(0,0,0)$	$-C_3$	$-C_{\Delta 2} + \gamma_2I - \lambda_2I + \xi_2R_c$	$-C_1$
$A(0,0,1)$	$-k_3C_3$	$-C_{\Delta 2} + \gamma_2I - \lambda_2I + \xi_2R_c$	C_1
$B(0,1,0)$	$\gamma_3I - \lambda_3I - C_3 + C_{\Delta 1}$	$C_{\Delta 2} - \gamma_2I + \lambda_2I - \xi_2R_c$	$-C_1$
$C(0,1,1)$	$\gamma_3I - \lambda_3I - k_3C_3 + C_{\Delta 1}$	$C_{\Delta 2} - \gamma_2I + \lambda_2I - \xi_2R_c$	C_1
$D(1,0,0)$	C_3	$\gamma_2I - \lambda_2I + \xi_2R_c$	$-C_1$
$E(1,0,1)$	k_3C_3	$\gamma_2I - \lambda_2I + \xi_2R_c$	C_1
$F(1,1,0)$	$\lambda_3I - \gamma_3I + C_3 - C_{\Delta 1}$	$\lambda_2I - \gamma_2I - \xi_2R_c$	$-C_1$
$G(1,1,1)$	$\lambda_3I - \gamma_3I + k_3C_3 - C_{\Delta 1}$	$\lambda_2I - \gamma_2I - \xi_2R_c$	C_1

Table 3. Conditions and state analysis of stable results.

Equilibrium Point	Real Signs of Eigenvalues of Jacobian Matrix	Condition	Stability
O(0,0,0)	(−, −, −)	$C_{\Delta 2} + \lambda_2 I > \gamma_2 I + \xi_2 R_c$	ESS
B(0,1,0)	(−, −, −)	$\lambda_3 I + C_3 > \gamma_3 I + C_{\Delta 1}, \gamma_2 I + \xi_2 R_c > C_{\Delta 2} + \lambda_2 I$	ESS
F(1,1,0)	(−, −, −)	$\gamma_3 I + C_{\Delta 1} > \lambda_3 I + C_3, \gamma_2 I + \xi_2 R_c > \lambda_2 I$	ESS

It can be seen from Table 3 that the system has three evolutionary stable points O(0,0,0), B(0,1,0), and F(1,1,0) in the conditional cases, namely (the designer's non-optimization, the contractor's non-optimization, and the owner's weak control), (the designer's non-optimization, the contractor's optimization, and the owner's weak control), and (the designer's optimization, the constructor's optimization, and the owner's weak control).

(1) By analyzing the three stability points, we can see a common feature that the owner chooses the choice of weak control. This is also in line with the basic requirements of the standard general contracting mode, which can explain why the FIDIC organization puts forward two situations in the general contracting mode (one is if the owners should closely supervise or control the work of the contractors or review most of the drawings, the other is the amount of each interim payment to be determined by the staff or other intermediaries) does not apply general contracting mode [35].

(2) When $\gamma_3 I + C_{\Delta 1} > \lambda_3 I + C_3$ and $\gamma_2 I + \xi_2 R_c > \lambda_2 I$, there is an evolutionary stable point F(1,1,0). In this case, the owner chooses weak control, and both the designer and the constructor choose optimization. This is the ideal result that the owner wants to see, which means that the main participants of the project maintain consistent goals and collaboration. The cooperation potential and professional ability of all parties can be stimulated, unnecessary internal friction can be avoided, the deep integration of the three core links of design, procurement, and construction can be truly realized, and the value added.

(3) When $C_{\Delta 2} + \lambda_2 I > \gamma_2 I + \xi_2 R_c$, there is an evolutionary stable point O(0,0,0). In this case, the owner chooses weak control, and both the designer and the constructor choose non-optimization, which often means that the designer and the constructor have reached a certain tacit agreement (such as using up all project budgets), and this tacit agreement can bring stable benefits to both sides. The reason for this situation is the lack of a benefit distribution mechanism or an unreasonable benefit distribution mechanism, so it is unable to motivate the designer and the constructor to choose optimization strategies. Therefore, it is necessary to adjust the design of the mechanism and incentive measures to make it evolve to the stable point F(1,1,0), to avoid the non-optimization strategy chosen by both the designer and the constructor, such as increasing the proportion of benefit sharing in the design optimization of the consortium, linking the implementation of design optimization with the payment of contract cost, and establishing a red and black list of cooperative contractors.

(4) When $\lambda_3 I + C_3 > \gamma_3 I + C_{\Delta 1}$, and $\gamma_2 I + \xi_2 R_c > C_{\Delta 2} + \lambda_2 I$, there is an evolutionary stable point B(0,1,0). In this case, although the designer does not choose to optimize, the constructor can re-delegate the professional designer to complete the design optimization work, and it will produce additional commission costs. Moreover, the re-employed designer is not familiar with the project requirements or design concepts. Although he can barely complete the design optimization task, defects may exist in interface processing, constructability, and connection with subsequent design schemes. Therefore, it is necessary to adjust the design of the mechanism or incentive measures to make it evolve to the stable point F(1,1,0), to avoid the non-optimization strategy chosen by the designer, such as increasing the distribution proportion of the designer's optimization design and establishing a long-term strategic cooperation relationship with the designer to change their expectations.

5. Case Study

5.1. Case Background

We selected the Yangtze River International Conference Center as the case project; this project adopts an engineering general contracting mode. The Nanjing Jiangbei New Area Management Committee has entrusted the Nanjing Jiangbei New Area Public Works Construction Center to construct the project. The Nanjing Jiangbei New Area Public Works Construction Center has entrusted Nanjing Urban Construction Management Group Co., Ltd., as the project management party, and entrusted Jiangsu Jianke Engineering Consulting Co., Ltd., to supervise the project. The Public Works Construction Center of Jiangbei New Area in Nanjing has entrusted the American Morphosis Architecture Firm to design the plan for the project and entrusted China Construction Eighth Engineering Bureau Co., Ltd., and Beijing Architectural Design and Research Institute Co., Ltd., to implement general contracting for the project. Jiangsu Kaiyuan Cost Consulting Co., Ltd., and Nanjing Jiankai Construction Project Management Co., Ltd., respectively, undertake the tracking audit and cost consulting work of this project. The specific roles and responsibilities of each party in this project are shown in Table 4 and Figure 5.

Table 4. Participants' information on the case project.

Serial Number	Participating Party	Name of Party
1	Owner	Nanjing Jiangbei New Area Public Works Construction Center (Nanjing, China)
2	Project Management consultant	Nanjing Urban Construction Management Group Corp., Ltd. (Nanjing, China)
3	Scheme Designer	Morphosis Architects (New York, United States of America)
3	Preliminary designer	China Construction Eighth Engineering Division Corp., Ltd. (Beijing, China)
5	Supervision consultant	Jiangsu Jianke Engineering Consulting Corp., Ltd. (Nanjing, China)
6	General contracting contractor (consortium)	China Construction Eighth Engineering Division Corp., Ltd. (Beijing, China) (Lead party) Beijing Institute of Architectural Design (Beijing, China)
7	Audit consultant	Jiangsu Kaiyuan Cost Consulting Corp., Ltd. (Nanjing, China)
8	Cost consultant	Nanjing Jiankai Construction Project Management Corp., Ltd. (Nanjing, China)

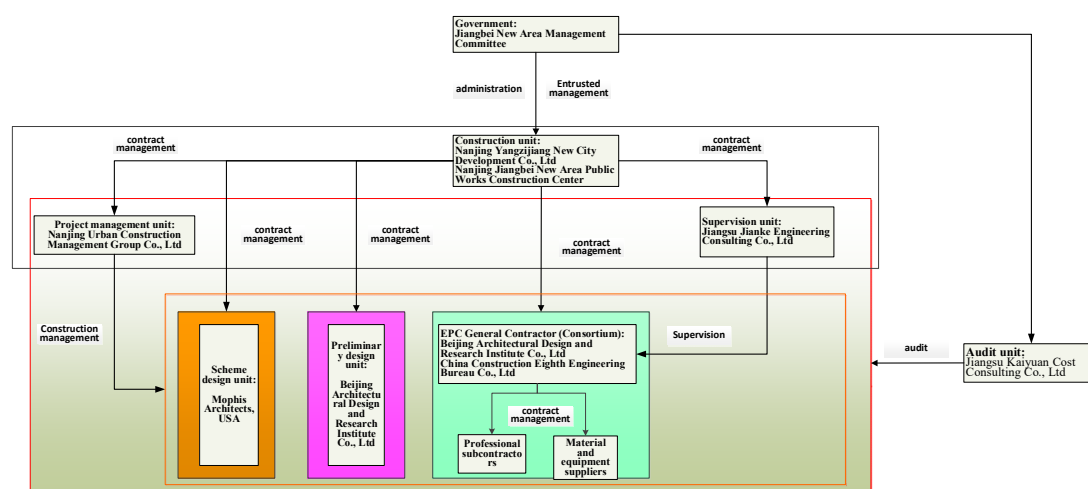


Figure 5. Schematic diagram of the relationship between all parties in the general contracting project of the Yangtze River International Convention Center. The red dashed line box denotes market entities for the general contracting project of the Yangtze River International Conference Center.

5.2. Parameter Value

Taking the XY general contracting project as a case study, the design optimization work is carried out. For some parameters without actual data, they are determined by contract data and expert discussion, as shown in Table 5.

Table 5. Main parameter values.

Serial Number	Parameters	Parameter Value	Unit	A Foundation for Value
1	I	585.0	Ten thousand CNY	Design optimization saves approximately 3% in costs
2	C_1	271.6	Ten thousand CNY	Conversion of supervision cost to roof engineering
3	k_3	1.1	—	Value based on the characteristics of the project
4	C_3	43.8	Ten thousand CNY	Conversion of optimized design costs to roof engineering
5	ξ_2	0.2	—	—
6	$C_{\Delta 1}$	10.0	Ten thousand CNY	Penalty borne by the designer when they are unable to complete the optimization work
7	$C_{\Delta 2}$	50.0	Ten thousand CNY	When the design party is unable to complete the optimization work setting, the lead party entrusts the design fee again

5.3. Numerical Simulation

Based on the theoretical analysis of the evolutionary game in Section 4, numerical simulations are carried out in combination with actual cases. In this case, the simulation of the probabilistic strategy selection of all parties is shown in Figure 6a.

(1) When the initial risk ratios assumed by the owner, design party, and construction party are set at 0.2, 0.4, and 0.4 (as members of a consortium, the design party, and the construction party should bear the same and joint liabilities), we observe the design optimization strategy choices of all parties. At this point, if the profit distribution ratios of the design party, the construction party (leading party of the consortium), and the owner are 0.6, 0.3, and 0.1 respectively, both the design party and the construction party choose to optimize, as shown in Figure 6b.

(2) If the profit distribution ratios of the design party, the construction party (leading party of the consortium), and the owner are 0.3, 0.6, and 0.1, respectively, the construction party still chooses to optimize, but the design party chooses not to optimize (as shown in Figure 6c). That is to say, the design party has a “psychological expectation” ratio for the distribution of optimization benefits. If the design party only receives a fixed design fee or the distribution of design optimization benefits is very low, the design party will give up choosing the design optimization strategy, even if there are incremental benefits in this situation. On the other hand, as the leading party of the consortium, the construction party still has enough enthusiasm to choose design optimization regardless of its profit distribution ratio.

(3) When the initial allocation ratios of benefits borne by the owner, the design party, and the construction party are set at 0.1, 0.3, and 0.6 (considering that the construction party is the leading party of the consortium and the main recipient of design optimization benefits), we observe the selection of design optimization strategies by all parties. At this point, regardless of the risk-sharing ratio between the design party, the construction party (leading party of the consortium), and the owner, the selection of design optimization strategies will not be affected, as shown in Figure 6d,e. In the Chinese context, the main factor determining the design optimization selection strategy for general contracting projects is the distribution ratio of benefits obtained from design optimization among the three parties.

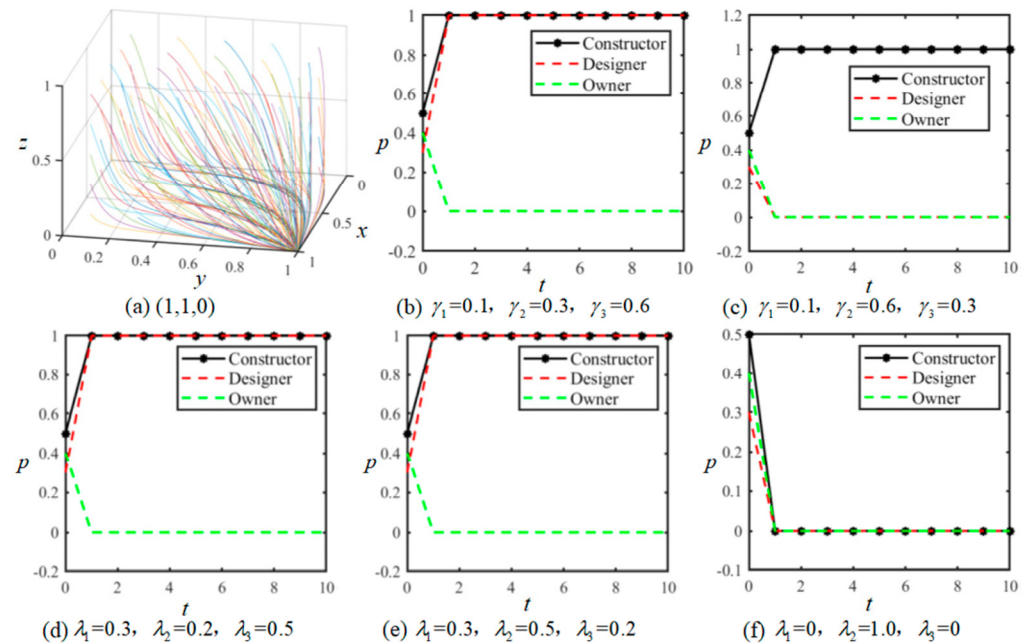


Figure 6. Numerical simulation of the general contracting project of the Yangtze River International Convention Center.

5.4. Discussion

(1) According to the numerical simulation of actual engineering cases, the risk-sharing ratio and benefit-sharing ratio are the key factors that affect the smooth optimization of the design of the general contract project. This is a noteworthy mechanical finding that the role of risk sharing and benefit distribution should be fully considered when planning the terms of the general contract. It is necessary to design an incentive mechanism that is in line with the Chinese context and has the effect of redistribution of risks and benefits and encourage the general contractor to take active measures to actively optimize the design and realize the deep integration of the three-core links of design, procurement, and construction. It is worth noting that in the follow-up research, it is possible to study how the risk-sharing ratio and benefit-sharing ratio affect the design optimization behavior when the designer and the construction party, respectively, act as the consortium leader.

(2) Owners should establish incentive contracts or incentive clauses. Because the general contracting project in the Chinese context adopts a settlement method based on facts under total price control, rather than a true total price contract, the general contractor only needs to not break through the controlled total price. In other words, in this case, the general contractor does not have enthusiasm for the deep integration and connection between design, procurement, and construction. Therefore, it is necessary to design an incentive mechanism for the engineering general contracting project in the Chinese context, to encourage the general contractor to actively take measures, actively carry out design optimization, and achieve deep integration of the core links of design, procurement, and construction, which is consistent with the findings of Zhang Hong, Wang, SW An Xi-aowei, [6,9,17], and others. Different from previous studies, this study analyzes the impact of different strategy choices of the three parties on the turnkey model from the perspective of carrying out design optimization. Specifically, this study argues that incentive contracts or incentive clauses should be established (such as allocation clauses for benefits brought about by the further optimization of scheme design) to fully reflect the advantages of the deep integration of general contracting mode design, procurement, and construction [36], allowing and encouraging the general contractor to propose reasonable suggestions and carry out design optimization, scheme optimization, plan optimization, etc., to save project investment and improve project quality. The scope of incentives for benefit sharing in the general contracting project design optimization is recommended to include cases where the

reduction in engineering volume exceeds the agreed percentage in the contract due to design optimization, cases where the reduction in investment exceeds the agreed percentage in the contract due to design optimization, cases where design optimization may reduce subsequent operating costs, and cases where design optimization accelerates construction and achieves early completion.

(3) The owner adjusts and optimizes the control method of the general contracting project. In theory, it has been proven that general contracting projects should adopt a “weak control approach” rather than a “strict control approach”, which conflicts with the current construction management system of engineering projects. Therefore, the owner should adjust and optimize the current control methods. For the design optimization of the general contracting project that involves quality, safety, environment, and other aspects, the “strict control method” should still be adopted. For the design optimization of the general contracting project that involves economic aspects, the “weak control method” should be adopted. In other words, under the general contracting mode, the owner should adhere to a single management function, focusing mainly on the owner’s needs and negative externality control, and adopting a loose control approach in other aspects [37,38]. The so-called externality control mainly refers to aspects such as project quality, safety, ecological environment, civilization, and arrears of migrant workers’ wages. To eliminate or reduce the impact of these negative externalities, owners should strengthen strict control over these negative externalities.

(4) The reason for the low proportion of general contracting projects, the limited number of successful cases, and the unsatisfactory implementation results lie in the phenomenon of “acclimatization” of international standard general contracting project design optimization theories and practices in the Chinese context. The proposal of this research question is based on three basic construction scenarios in China: firstly, China’s general contracting project owners bear a lot of risks, which makes the consortium’s enthusiasm for design optimization low; secondly, China’s general contracting project owners adopt a strong control approach, resulting in insufficient space for the consortium to carry out design optimization; and thirdly, the general contracting project owners lack sufficient enthusiasm to carry out design optimization. It is difficult to implement the theory and practice of risk sharing under the international standard general contracting mode in China’s general contracting projects. Considering the current characteristics of China’s construction market, the general contractor still has shortcomings in risk awareness, risk control ability, and level. In addition, the engineering guarantee and insurance system cannot fully meet the requirements of risk sharing under the international standard general contracting mode [39,40]. Therefore, the general contracting project risk should not be borne solely or mainly by the general contractor, but should be reasonably allocated between the owner and the general contractor based on the risk type of the general contracting project, the nature of risks, and the risk-bearing capacity of the owner and the general contractor, combined with the basic principles of general contracting project risk sharing [41–43].

6. Conclusions

(1) From the calculation of evolutionary game theory and practical case applications, it can be seen that a weak control strategy is the basic principle that general contracting projects should follow and is the key to the smooth implementation and application of this model. It is also a basic requirement for both construction and design parties to choose design optimization in the context of a consortium. In addition, based on engineering practice and industry characteristics, when participating in general contracting projects in the form of a consortium, the leading party generally has design optimization motivation, while the participating parties generally rarely actively carry out design optimization. Contract design is crucial.

(2) Considering the objective existence of the Chinese context and the requirements of engineering practice, within a certain range and constraint conditions (the specific formula is omitted), the construction party and the design party may have different strategic

choices, that is, they do not always choose design optimization, and they also require incentives from the owner. In other words, the incentive, risk allocation coefficient, and value-added sharing coefficient of the owner are the key factors for the stable existence of design optimization. The theoretical calculation results based on evolutionary game theory indicate the following: firstly, adopting a “weak control” strategy is the optimal choice for the owners under the general contracting mode; secondly, the distribution ratio of the benefits obtained from the general contracting project design optimization activities is a key influencing factor in determining the strategic choices of all parties; and thirdly, there are multiple evolutionary stable points in the system, which inspires the general contracting project management in the Chinese context by guiding participants to choose ideal policies that maximize project benefits through mechanism design or incentive measures.

The study on the tripartite evolutionary game and stability strategy of the general contracting project consortium considers the scenario where the contractor is the leading party, and future research will focus on the issue of the tripartite evolutionary game and stability strategy under the scenario where the designer is the leading party.

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