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A TRIPARTITE EVOLUTIONARY GAME INVOLVING QUALITY REGULATION OF PREFABRICATED BUILDING PROJECTS CONSIDERING GOVERNMENT REWARDS AND PENALTIES

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In recent years, there have been great efforts to develop prefabricated buildings and to promote the EPC mode. However, various types of construction quality accidents have frequently occurred, and the emergency management agency reported 272 prefabricated construction accidents in China between 2018 and 2022. To improve the quality regulation of prefabricated buildings, this paper constructs a tripartite evolutionary game model of the government, EPC general contractors, and supervision units. It analyzes the stability of the evolutionary strategies of all parties involved, and it tests the influence of the reward and punishment mechanism, rent-seeking costs, and other factors on the choice of tripartite strategies through simulation. The results show the following: When government regulators increase the punishment and set reasonable reward quotas, EPC general contractors choose to standardize construction, and supervision units supervise strictly. EPC general contractors and supervision units evolve in a positive direction if the sum of rewards and punishments is higher than the gains from speculation. Government regulation evolves to be stricter if higher authorities increase the punishment for lack of regulation.

Keywords: Prefabricated Buildings; Quality Regulation; EPC Mode; Tripartite Evolutionary Game

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1. INTRODUCTION

Currently, China's construction industry is experiencing problems with high consumption, high pollution, and low efficiency in the traditional housing construction process (Chastas *et al*., 2018). With the increasingly strict requirements for environmental protection and energy conservation, the upgrading and transformation of traditional buildings are also imminent (Coma *et al*., 2020). Construction industrialization is a new construction production method to achieve the transformation and upgrading of the construction industry and sustainable development (Wang *et al*., 2020). Prefabricated buildings are an important way to implement construction industrialization (Sha *et al*., 2021). In September 2016, the General Office of the State Council issued the "Guidance on the vigorous development of prefabricated buildings", which specifies multiple tasks, such as improving the standard specification system for prefabricated buildings, upgrading the construction level of prefabricated buildings, implementing the engineering procurement construction (EPC) general contracting mode, and ensuring project quality and safety. In January 2022, the Ministry of Housing and Construction issued the 14th Five-Year Plan for the development of the construction industry, which proposes vigorously developing prefabricated buildings, increasing the application of intelligent manufacturing in all aspects of construction, and improving project safety, efficiency, and quality. Meanwhile, the plan requires creating an internet platform for the construction industry, building a government regulatory platform, increasing the incentives for trustworthiness and penalties for failure to trust, and comprehensively improving the level of engineering quality and safety supervision.

The highly modular construction method (Thisari *et al*., 2022) has set new requirements for the quality management of prefabricated buildings. However, the quality management system is still immature, and the number of skilled construction personnel is insufficient, as there are many potential problems in the quality of prefabricated building projects (Zhang and Tsai, 2021). Due to the lack of related experience in prefabricated buildings, there are still some unavoidable quality defects

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in the process of constructing prefabricated buildings (Duan *et al*., 2020). The regulation of prefabricated buildings in China is still in the development stage (Dou *et al*., 2019). Provincial and municipal government departments have also successively introduced trial measures regarding the regulation of prefabricated buildings (Zhao and Chen, 2022).

However, although government departments have introduced pilot measures, the problem of ineffective regulation remains unresolved. In fact, due to the lack of government supervision ability in the professional field, the government supervision mechanism is difficult to fundamentally implement (Zhang *et al*., 2023). From the perspective of ensuring construction quality, third-party supervision units, as an auxiliary force that compensates for the government's insufficient supervision ability in the professional field, have become the judge of the quality of prefabricated buildings (Li and Yin, 2020; Xu, 2020). Driven by interests, supervision units have the risk of agreeing to engage in rent-seeking, with the result being that the quality of prefabricated buildings falls short of government requirements (Cheng *et al*., 2019). Therefore, the main objective of this paper is to construct a three-way evolutionary game model to investigate the mechanism of influence among the three stakeholders of an EPC general contractor, supervision unit, and government regulator (Friedman, 1991). To better achieve the research objective of this paper, we focus on addressing the following questions: (1) What is the payoff matrix of the tripartite evolutionary game model considering rent-seeking behavior? (2) What are the impacts of government reward and punishment mechanisms on the choice of behavioral strategies of the three stakeholders? (3) What are the evolutionary stable strategies (ESS) of the three stakeholders? Thus, this paper focuses on exploring the conditions for the three stakeholders to achieve a stable equilibrium strategy through model construction and simulation experiments and then proposes several management insights and suggestions.

The rest of this paper is organized as follows. In Section 2, we discuss the literature related to prefabricated buildings and evolutionary games. In Section 3, we construct an evolutionary game model and introduce the assumptions, variables and parameters of the model in detail. In Section 4, we present the analytical results of an ESS in the evolutionary game model. In Section 5, we simulate the results of the analysis to simulate the actual situation and present the simulation results. In Section 6, we summarize the conclusions, provide the managerial implications of this paper and indicate further research directions.

2. LITERATURE REVIEW

In recent years, scholars have conducted related research on the factors that affect the quality of prefabricated buildings. Wuni and Shen (2019) stated that prefabricated construction is better than traditional construction, but it is important to master the key factors, including using experienced workers, skilled management teams, reliable transportation equipment, etc. Luo, Xue *et al*. (2021) integrated and proposed a body of knowledge that can cover a wide range of research and activities related to assembled buildings, which is important for guiding practitioners in their related research and activities. In terms of identifying and controlling influencing factors, Xia *et al*. (2021) summarized the critical factors that affect the quality management of prefabricated construction, distinguished the key risks and improved the effect of project risk control. Yadi and Guanlei (2020) explored the mechanism of action among the quality factors and proposed corresponding preventive measures after investigating and studying the construction sites of prefabricated buildings. Jingyang *et al*. (2022) constructed an external benefit evaluation index system from the economic, environmental and social dimensions.

Through quantitative research, a quantitative evaluation model of a prefabricated building was designed. Information technology has also been gradually applied to the quality management of prefabricated buildings. Zhong and Qin (2022) used building information modeling (BIM) technology for construction management during the construction process to achieve safe site management and construction, reduce unnecessary errors in human operations and improve construction quality. Lihui *et al*. (2022), based on BIM technology, improved the efficiency of prefabricated assembly and hoisting scheduling, reduced the process and cost and improved the quality. Yan *et al*. (2022) combined a computer-based vision technique, weighted kernel density estimation method and acquisition time management method for the intelligent monitoring and evaluation of prefabricated building construction scheduling to open new ideas to improve the quality of prefabricated building construction. Most existing results focus on an objective analysis of engineering quality, which only verifies that these factors affect the quality of prefabricated buildings. However, it is difficult to explain why there are still intentional violations despite the continuous improvement in quality standards and the increasing level of management. The project quality of prefabricated buildings is closely related to the quality behavior of the project participants, and quality control should focus on the logic of the main actors in the system and their behavioral strategies. The main purpose of implementing quality supervision for prefabricated building projects is to regulate the quality behavior of the participating actors to guarantee the quality of the entire project.

Evolutionary game theory (Lewontin, 1961) constitutes an effective method for studying the behavioral decisions of multiple subjects by using a finite rational game as an analytical framework and achieving the dynamic equilibrium of the game through the continuous learning of the multiple subjects of the game (Hammerstein, 2002). Unlike traditional game theory, which assumes that the subject is perfectly rational and has complete information, in an evolutionary game, the subject often adjusts his or her strategy by observing the strategic behavior of other subjects (Samuelson, 2002). As a result, the game subject has many uncertainties in strategy selection. In recent years, evolutionary games have been widely used in the study of various industries. For example, Ullah *et al*. (2021) took a maintenance service as the research object and established a utility function model of the enterprise. By using game theory, the optimal sale price and warranty period for the manufacturer can be determined. Chung *et al*. (2018) suggested a collaboration model to increase the competitiveness of every participating company through a monopoly of service centers and the sharing of consolidation terminals. On the basis of game theory, a systematic approach is used to assign the theory of each participating company. Yuan *et al*. (2022) explored evolutionary decision-making behaviors and stable strategies of the government, real estate developers and home buyers in the prefabricated construction industry and proposed an orderly and sustainable development mechanism. Shi *et al*. (2022) considered subsidy and carbon tax policies, and an evolutionary game model was established to provide practical enlightenment for the government to achieve low-carbon, green, and sustainable construction. Mengwei, Junwu, Xiang *et al*. (2022) established the dynamic evolution model of prefabricated construction cost risk and studied the evolution and transfer mechanism of cost risk during project implementation. Zhang *et al*. (2022) proposed an evolutionary game model for construction safety regulation and used system dynamics for a simulation analysis to provide a theoretical reference for improving the construction safety regulation system of prefabricated buildings. Li *et al*. (2020) developed new models to determine the revenue risk related to the use of prefabricated buildings, and the results show that the key to promoting the development of prefabricated building projects is to increase the incremental income of developers in projects. Since prefabricated buildings have higher costs than traditional buildings, the participating parties may be driven by interests to play between building quality and economic benefits. It follows that evolutionary game theory is an effective tool for solving such problems. Evolutionary game theory abandons the assumption of complete rationality, and it takes Darwinian biological evolution as its conceptual basis. Starting from system theory, evolutionary game theory regards the process of adjusting group behavior as a dynamic system in which each individual's behavior and the relationship between the group members are described separately, forming a macro model with a micro basis. Therefore, the combination of this study and evolutionary game theory can more truly reflect the diversity and complexity of behavioral agents and can provide a theoretical basis for the macro control of group quality behavior.

Accordingly, the literature makes some theoretical contributions to prefabricated building quality and evolutionary games, but the following problems remain. (1) Few articles have combined the quality regulation of prefabricated buildings with evolutionary games. (2) Few scholars include rent-seeking behavior in the scope of model consideration, and theoretical research is not sufficiently relevant to reality. (3) Most existing results focus on an objective analysis of engineering quality, but few scholars have focused on the logic of the stakeholders in the system and their behavioral strategies. This paper considers the possible rent-seeking behaviors of EPC general contractors and supervisors who are driven by interests and constructs a three-way evolutionary game model that consists of the EPC general contractors, supervision units, and government regulators. To solve these three problems, the paper combines quality regulation with an evolutionary game, incorporates rent-seeking behavior into the scope of the model, and focuses on the behavioral strategies of the participants. The strategy stability of each game party and the influence of each element on strategy selection are analyzed, and the stable state and convergence of each evolutionary equilibrium solution are analyzed through a simulation, which can improve the effect of the government regulator on the quality of the prefabricated construction industry and regulate the quality behavior of each participating subject. This study fills part of the gap in the quality regulation of prefabricated buildings and provides countermeasures and suggestions to improve the quality and safety supervision system for such buildings to ensure the development of high-quality prefabricated buildings.

3. MODEL ASSUMPTIONS AND CONSTRUCTION

The logical relationships among the subjects of the tripartite evolutionary game constructed in this paper for the quality supervision of prefabricated building projects are shown in Figure 1.

3.1 Model assumptions

To construct the game model and analyze the stability of each party's strategy and equilibrium point and the influence of each element, the following assumptions are made.

Assumption 1. The prefabricated building EPC general contractor is Participant 1, the prefabricated building supervision unit is Participant 2, and the government regulator is Participant 3. All three parties are finitely rational participants, and the strategy choice gradually evolves and stabilizes over time at the optimal strategy.

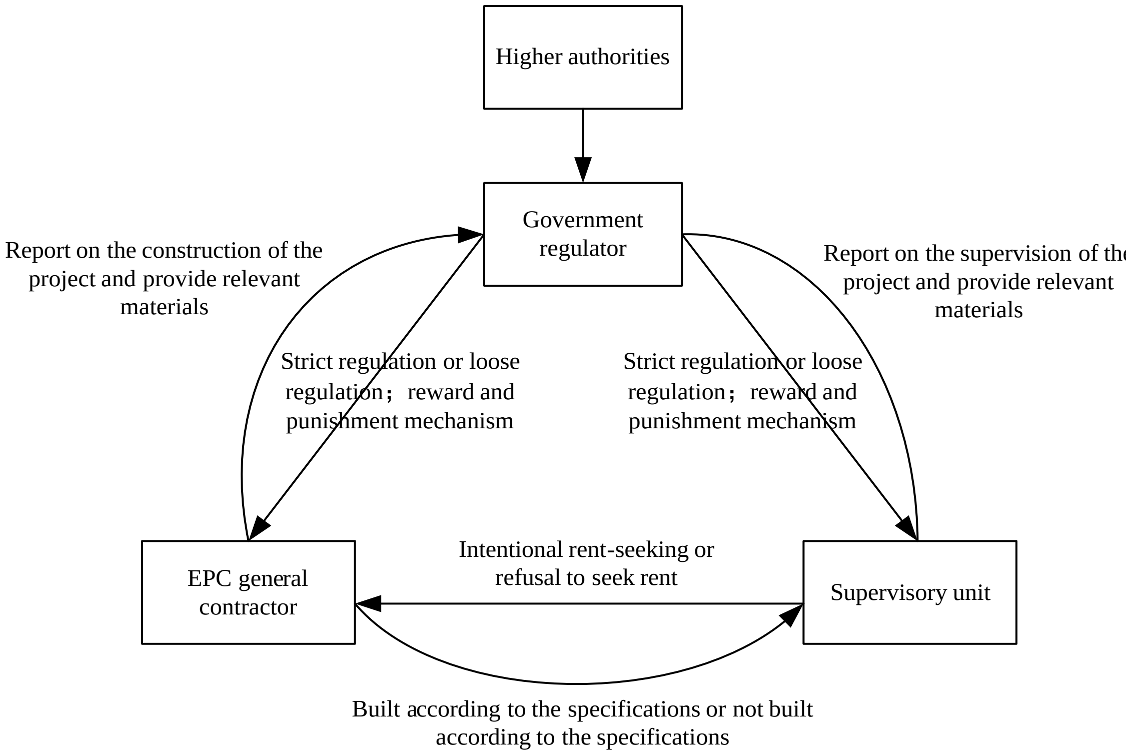

Figure 1. The description of the relationships in the evolutionary game.

Assumption 2. For the EPC general contractor of prefabricated buildings, the strategy space α = (α_1, α_2) = (built according to the specifications, not built according to the specifications). The probability that α_1 is chosen is x, and the probability that α_2 is chosen is $(1-x), x \in [0,1]$. For the prefabricated construction supervision unit, the strategic space β=(β_1, β_2)=(strict supervision, loose supervision). The probability that β_1 is chosen is y and the probability that β_2 is chosen is $(1-y), y \in [0,1]$. For the government regulator, the strategy space $\gamma = (\gamma_1, \gamma_2)$=(strict regulation, loose regulation). The probability that γ_1 is chosen is z, and the probability that γ_2 is chosen is $(1-z), z \in [0,1]$.

Assumption 3. The total revenue after the completion and acceptance of the construction project is R_c. The cost of the EPC general contractor to build according to the specifications is C_{cg}, and the cost of not building according to the specifications is C_{cb}. When the EPC general contractor unit is built according to the specifications, it can pass the inspection of the supervisory unit, and when the EPC general contractor is not built according to the specifications, it will engage in rent-seeking from the supervisory unit to pass the inspection. The cost of engaging in rent-seeking is B_b, $B_b < \left(C_{cg} - C_{cb}\right)$, and a building that is not constructed according to the specifications will incur speculative cost T_c.

Assumption 4. The construction work needs to be accepted by the owner and the supervisory unit after completion to be considered complete, and the revenue of the supervisory unit is R_m. The cost of strict supervision by the supervisory unit is C_{mh}, and the cost of loose supervision by the supervisory unit is C_{ml}. When the EPC general contractor does not build according to the specifications if the supervision unit refuses to engage in rent-seeking, then the contractor cannot receive approval, and if the supervision unit engages in rent-seeking to help the EPC general contractor receive approval, then the speculative cost of the supervision unit engaging in rent-seeking is T_m.

Assumption 5. The cost of strict government regulation is C_{gh}. When the government strictly regulates, if the EPC general contractor does not build according to the specifications, then it will be fined F_c, and the supervision unit will be fined F_m for loose supervision. If the EPC general contractor is rewarded J_c for building according to the specifications, then the supervisory unit will be rewarded J_m for strict supervision. The cost of loose government regulation is C_{gl}, and when the regulation is loose, the government regulator does not issue rewards or penalties.

Assumption 6. The EPC general contractor's standardized construction and the supervisory unit's strict supervision are conducive to economic development and social stability and bring R_g benefits to the government. When the EPC general contractor does not build according to the specifications, when the supervision unit intends to seek rent, and when quality and safety accidents occur, the government spends D_g to maintain social stability and rectify the construction industry. The government regulator adopts a loose regulatory strategy that leads to a lack of regulation, and when quality and safety accidents occur, the government regulator is held accountable by higher authorities with a fine of E_g.

3.2 Model Construction

Based on the above assumptions, the tripartite payoff matrix of the EPC general contractor, supervisor and government regulator is shown in Table 1.

Table 1. The tripartite payoff matrix

Supervisory unit			Government regulator	
			Strict regulation (z)	Loose regulation $(1-z)$
EPC general contractor	Built according to the specifications (x)	Strict supervision (y)	$R_c - C_{cg} + J_c$, $R_m - C_{mh} + J_m$, $-C_{gh} - J_c - J_m + R_g$	$R_c - C_{cg}$,$R_m - C_{mh}$,$-C_{gl} + R_g$
		Loose supervision $(1-y)$	$R_c - C_{cg} + J_c$, $R_m - C_{ml} - T_m - F_m$,$-C_{gh} - J_c + F_m$	$R_c - C_{cg}$,$R_m - C_{ml} - T_m$,$-C_{gl}$
	Not built according to the specifications $(1-x)$	Strict supervision(y)	$-C_{cb} - T_c - F_c$, $R_m - C_{mh} + J_m$, $-C_{gh} + F_c - J_m$	$-C_{cb} - T_c$,$R_m - C_{mh}$,$-C_{gl}$
		Loose supervision $(1-y)$	$R_c - C_{cb} - B_b - T_c - F_c$,$R_m - C_{ml} - T_m + B_b - F_m$,$-C_{gh} + F_c + F_m - D_g$	$R_c - C_{cb} - B_b - T_c$, $R_m - C_{ml} - T_m + B_b$,$-C_{gl} - D_g - E_g$

4. MODEL ANALYSIS

4.1 Analysis of The Stable Strategy of The EPC General Contractor

The expected revenue of the EPC general contractor from building E_{11} and not building E_{12} according to the specifications and the average revenue expectation $\overline{E_1}$ are as follows:

$$E_{11} = yz(R_c - C_{cg} + J_c) + y(1-z)(R_c - C_{cg}) + (1-y)z(R_c - C_{cg} + J_c) + (1-y)(1-z)(R_c - C_{cg}) \tag{1}$$

$$\begin{aligned} E_{12} &= yz(-C_{cb} - T_c - F_c) + y(1-z)(-C_{cb} - T_c) + (1-y)z(R_c - C_{cb} - B_b - T_c - F_c) \\ &+(1-y)(1-z)(R_c - C_{cb} - B_b - T_c) \end{aligned} \tag{2}$$

$$\overline{E_1} = xE_{11} + (1-x)E_{12} \tag{3}$$

The replication dynamic equation of the strategy selection of the EPC general contractor is as follows:

$$\begin{aligned} F(x) &= \frac{dx}{dt} = x(E_{11} - \overline{E_1}) = x(1-x)(E_{11} - E_{12}) \\ &= x(x-1)\left[C_{cg} - C_{cb} - B_b - T_c + y(B_b - R_c) - z(F_c + J_c)\right]\#(4) \end{aligned} \tag{4}$$

The first-order derivatives of x and set $G(y)$ are the following:

$$\frac{d(F(x))}{dx} = (2x-1)\left[C_{cg} - C_{cb} - B_b - T_c + y(B_b - R_c) - z(F_c + J_c)\right] \tag{5}$$

Set

$$G(y) = C_{cg} - C_{cb} - B_b - T_c + y(B_b - R_c) - z(F_c + J_c) \tag{6}$$

When $y = \frac{C_{cg} - C_{cb} - B_b - T_c - z(F_c + J_c)}{(R_c - B_b)} = y^*$, $G(y) = 0$, and $F(x) = 0$. Thus, all values of x are in an evolutionary steady state.

According to the stability theorem of the differential equation, the probability that the EPC general contractor will choose to build according to the specifications is in a stable state that must satisfy $F(x) = 0$ and $\frac{d(F(x))}{dx} < 0$. Since $\frac{\partial G(y)}{\partial y} < 0$, $G(y)$ is a decreasing function with respect to y. Therefore, when $y < y^*$, $G(y) > 0$. When $\frac{d(F(x))}{dx|_{x=0}} < 0$ and $F(x)|_{x=0} = 0$, at this time, $y = 0$ is the ESS of the EPC general contractor. Similarly, when $y > y^*$, we can obtain $x = 1$ as the ESS. Assume a three-dimensional space: $M = \{D(x, y, z)|0 \leq x \leq 1, 0 \leq y \leq 1, 0 \leq z \leq 1\}$. When the initial state of the game lies within space V_{A_1}, the EPC general contractor will eventually evolve to not build according to the specifications. When the initial state of the game lies within space V_{A_2}, the EPC general contractor will eventually evolve to build according to the specifications. Based on the above analysis process, the evolutionary phase diagram of the strategy of the EPC general contractor is drawn, as shown in Figure 2.

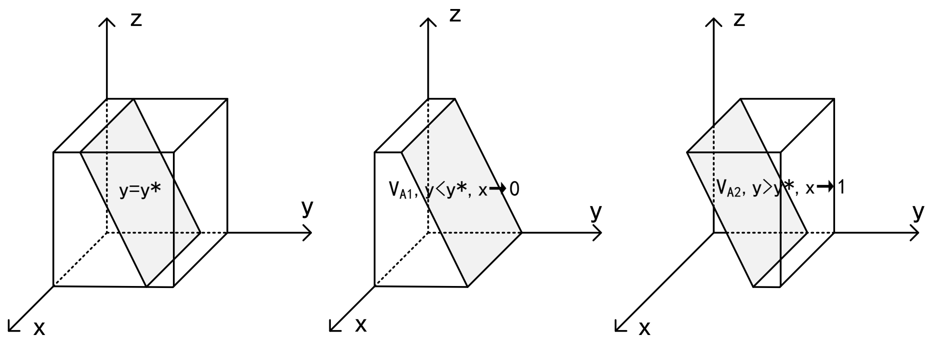

Figure 1. The evolutionary phase diagram of the strategy of the EPC general contractor.

The figure shows that the probability of the EPC general contractor not building according to the specifications is the volume V_{A_1} of A_1, and the probability of building according to the specifications is the volume V_{A_2} of A_2. The calculation is obtained as follows:

$$V_{A_1} = \int_0^1 \int_0^1 y^* dz dx = \int_0^1 \int_0^1 \frac{C_{cg} - C_{cb} - B_b - T_c - z(F_c + J_c)}{R_c - B_b} dz dx = \frac{2(C_{cg} - C_{cb} - B_b - T_c) - (F_c + J_c)}{2(R_c - B_b)} \tag{7}$$

$$V_{A_2} = 1 - V_{A_1} = \frac{(F_c + J_c) - 2(C_{cg} - C_{cb} - R_c - T_c)}{2(R_c - B_b)} \tag{8}$$

Corollary 1. The probability of the EPC general contractor building according to the specifications is positively correlated with the completion revenue, speculative costs, and government incentives and penalties and negatively correlated with the cost savings for the EPC general contractor not building according to the specifications.

Proof. According to the expression of the probability V_{A_2} that the EPC general contractor will build according to the specifications, we find the first-order partial derivative of each element. $\frac{\partial V_{A_2}}{\partial R_c} > 0$, $\frac{\partial V_{A_2}}{\partial B_b} > 0$, $\frac{\partial V_{A_2}}{\partial T_c} > 0$, $\frac{\partial V_{A_2}}{\partial (F_c + J_c)} > 0$, and $\frac{\partial V_{A_2}}{\partial (C_{cg} - C_{cb})} < 0$. Therefore, when R_c, T_c, or $(F_c + J_c)$ increases or $(C_{cg} - C_{cb})$ decreases, the probability that the EPC general contractor will build according to the specifications increases.

Corollary 1 shows that for the EPC general contractor, securing the completion revenue prevents the contractor from not building according to the specifications. The government regulator increases the incentive subsidy for the EPC general contractor to build according to the specifications and increases the penalty for the EPC general contractor for not building according to the specifications, which enables contractors to improve the quality of their projects through standardized construction. The government regulator can also increase the speculative cost of the EPC general contractor for not building according to the specifications by promoting the information construction of construction projects and expanding the influence of the media to encourage the EPC general contractor to build according to the specifications.

Corollary 2. The probability of the EPC general contractor building, according to the specifications, increases with the probability of strict supervision by the supervision unit and with the probability of strict supervision by the government regulator.

Proof. The analysis of the stability of the EPC general contractor's strategy shows that when $y < \frac{[C_{cg}-C_{cb}-B_b-T_c-z(F_c+J_c)]}{(R_c-B_b)}$ or $z < \frac{[C_{cg}-C_{cb}-B_b-T_c+y(B_b-R_c)]}{F_c+J_c}$, $G(y) > 0$. At this point, $\frac{d(F(x))}{dx|_{x=0}} < 0$ and $F(x)|_{x=0} = 0$. Thus, $x = 0$ is the ESS of the EPC general contractor. Similarly, when $y > \frac{[C_{cg}-C_{cb}-B_b-T_c-z(F_c+J_c)]}{(R_c-B_b)}$ or $z > \frac{[C_{cg}-C_{cb}-B_b-T_c+y(B_b-R_c)]}{F_c+J_c}$, $G(y) < 0$. At this point, $\frac{d(F(x))}{dx|_{x=1}} < 0$, and $F(x)|_{x=1} = 0$. Thus, $x = 1$ is the ESS of the EPC general contractor. Therefore, with the gradual increase in y and z, the stable strategy of the EPC general contractor increases from $x = 0$ (not built according to the specifications) to $x = 1$ (built according to the specifications).

Corollary 2 shows that increasing the probability of strict supervision by the supervisory unit predisposes the EPC general contractor to choose a building according to the specifications as a stable strategy. Similarly, when government regulators increase the probability of strict regulation, they can prompt the EPC general contractor to build according to the specifications as a stable strategy. Therefore, when the supervision unit strictly supervises, and the local government strictly regulates, the EPC general contractor building according to the specifications will receive higher incentives and subsidies, and at this time, the contractor will tend to choose the stable strategy of building according to the specifications.

4.2 Analysis of the Stable Strategy of The Supervision Unit

The expected revenue of the supervisory unit from strict supervision E_{21} and loose supervision E_{22} and the average expected revenue $\overline{E_2}$ are as follows:

$$E_{21} = xz(R_m - C_{mh} + J_m) + x(1-z)(R_m - C_{mh}) + (1-x)z(R_m - C_{mh} + J_m) + (1-x)(1-z)(R_m - C_{mh}) \tag{9}$$

$$\begin{aligned} E_{22} &= xz(R_m - C_{ml} - T_m - F_m) + x(1-z)(R_m - C_{ml} - T_m) \\ &+ (1-x)z(R_m - C_{ml} - T_m + B_b - F_m) + (1-x)(1-z)(R_m - C_{ml} - T_m + B_b) \end{aligned} \tag{10}$$

$$\overline{E_2} = yE_{21} + (1-y)E_{22} \tag{11}$$

The replication dynamic equation of the strategy selection of the supervision unit is as follows:

$$\begin{aligned} F(y) &= \frac{dy}{dt} = y(E_{21} - \overline{E_2}) = y(1-y)(E_{21} - E_{22}) \\ &= y(y-1)[C_{mh} + B_b - C_{ml} - T_m - xB_b - z(F_m + J_m) - xz(C_{mh} - C_{ml})] \end{aligned} \tag{12}$$

The first-order derivatives of y and set $H(z)$ are the following:

$$\frac{d(F(y))}{dy} = (2y-1)\begin{bmatrix} C_{mh} + B_b - C_{ml} - T_m - xB_b \\ -z(F_m + J_m) - xz(C_{mh} - C_{ml}) \end{bmatrix} \tag{13}$$

Set

$$H(z) = C_{mh} + B_b - C_{ml} - T_m - xB_b - z(F_m + J_m) - xz(C_{mh} - C_{ml}) \quad ()$$

When $z = \frac{C_{mh}+B_b-C_{ml}-T_m-xB_b}{F_m+J_m+x(C_{mh}-C_{ml})} = z^*$, $H(z) = 0$, and $F(y) = 0$. Thus, all values of x are in an evolutionary steady state.

According to the stability theorem of the differential equation, the probability that the supervisory unit selects strict supervision and is in a stable state must satisfy $F(y) = 0$ and $\frac{d(F(y))}{dy} < 0$. Since $\frac{\partial H(z)}{\partial z} < 0$, $H(z)$ is a decreasing function with respect to z. Therefore, when $z < z^*$, $H(z) > 0$. When $\frac{d(F(y))}{dy|_{y=0}} < 0$ and $F(y)|_{y=0} = 0$, at this time, $y = 0$ is the ESS of the supervisory unit. Similarly, when $z > z^*$, we obtain $y = 1$ as the ESS. Assume a three-dimensional space: $M = \{D(x, y, z)|0 \leq x \leq 1, 0 \leq y \leq 1, 0 \leq z \leq 1\}$. When the initial state of the game lies within space V_{B_1}, the supervisory unit will eventually evolve to carry out loose supervision. When the initial state of the game lies within space V_{B_2}, the supervisory unit will eventually evolve to carry out strict supervision. Based on the above analysis process, the evolutionary phase diagram of the strategy of the supervisory unit is drawn, as shown in Figure 3.

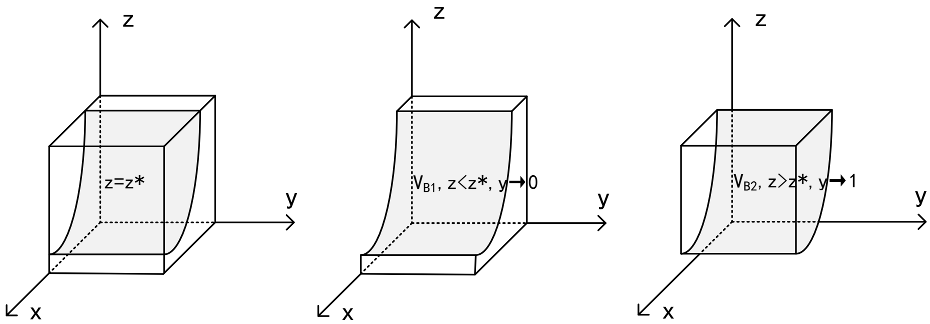

Figure 2. The evolutionary phase diagram of the strategy of the supervisory unit.

Corollary 3. The probability of strict supervision by the supervisory unit is positively correlated with the regulator's fine for loose supervision, the reward for strict regulation, and the speculative cost of the supervisory unit's engagement in rent-seeking and negatively correlated with the cost saved by loose supervision and the gain obtained by engaging in rent-seeking.

Proof. The first-order partial derivatives of each element are found separately for V_{B_2}, $\frac{\partial V_{B_2}}{\partial(J_m)} > 0$, $\frac{\partial V_{B_2}}{\partial(T_m)} > 0$, $\frac{\partial V_{B_2}}{\partial(F_m)} > 0$, $\frac{\partial V_{B_2}}{\partial(C_{mh}-C_{ml})} < 0$, and $\frac{\partial V_{B_2}}{\partial(B_b)} < 0$. Therefore, any increase in J_m, T_m, or F_m or decrease in $(C_{mh} - C_{ml})$ and B_b can increase the probability of strict supervision by the supervisory unit.

Corollary 3 shows that when the supervisory unit intends to gain more from rent-seeking, it will conduct loose supervision. At this time, the government regulator should strengthen its supervision of the supervisory unit. If the government regulator increases the penalties for loose supervision and the rewards for strict supervision, then such increases can make the supervisory unit enforce strict supervision. In addition, the probability of strict supervision can also be enhanced by increasing the speculative cost of supervision units through the information construction of construction projects and by improving the professionalism of personnel. Severe punishment can effectively guarantee the quality and safety of prefabricated buildings, and a reasonable reward can also encourage the supervisory unit to strictly supervise and develop a good atmosphere for the development of prefabricated buildings.

Corollary 4. The probability of strict supervision by the supervisory unit increases with the probability of the EPC general contractor building according to the specifications or the probability of strict supervision by the government regulator.

Proof. The analysis of the stability of the supervisory unit's strategy shows that when $z < \frac{C_{mh}+B_b-C_{ml}-T_m-xB_b}{F_m+J_m+x(C_{mh}-C_{ml})}$ or $x < \frac{(C_{mh}+B_b-C_{ml}-T_m-z(F_m+J_m))}{(z(C_{mh}-C_{ml})+B_b)}$, $H(z) > 0$. At this point, $\frac{d(F(y))}{dy|_{y=0}} < 0$, and $F(y)|_{y=0} = 0$. Thus, $y = 0$ is the ESS of the supervisory unit. Similarly, when $z > \frac{C_{mh}+B_b-C_{ml}-T_m-xB_b}{F_m+J_m+x(C_{mh}-C_{ml})}$ or $x > \frac{(C_{mh}+B_b-C_{ml}-T_m-z(F_m+J_m))}{(z(C_{mh}-C_{ml})+B_b)}$, $H(z) < 0$. At this point, $\frac{d(F(y))}{dy|_{y=1}} < 0$, and $F(y)|_{y=1} = 0$. Thus, $y = 1$ is the ESS of the supervisory unit. Therefore, with the gradual increase in x and z, the stable strategy of the supervisory unit increases from $y = 0$ (loose supervision) to $y = 1$ (strict supervision).

Corollary 4 shows that increasing the probability of the EPC general contractor building according to the specifications is conducive to the supervisory unit choosing strict supervision as a stable strategy. Similarly, when the government regulator increases the probability of strict supervision, it can also encourage the supervisory unit to adopt strict supervision as a stable strategy. Therefore, when the EPC general contractor builds according to the specifications and the local government strictly supervises, the supervisory unit with strict supervision will receive higher incentives and subsidies, and at this time, it will tend to choose the stable strategy of strict supervision.

4.3 Analysis of The Stable Strategy of The Government Regulator

The expected revenue of the government regulator from strict regulation E_{31} and loose regulation E_{32} and the average expected revenue $\overline{E_3}$ are as follows:

$$E_{31} = xy(-C_{gh} - J_c - J_m + R_g) + x(1-y)(-C_{gh} - J_c + F_{\mathrm{m}}) + +(1-x)y(-C_{gh} + F_c - J_m) \\ +(1-x)(1-y)(-C_{gh} + F_c + F_{\mathrm{m}} - D_g) \tag{15}$$

$$E_{32} = xy(-C_{gl} + R_g) + x(1-y)(-C_{gl}) + (1-x)y(-C_{gl}) + (1-x)(1-y)(-C_{gl} - D_g - E_g) \tag{16}$$

$$\overline{E_3} = zE_{31} + (1-z)E_{32} \tag{17}$$

The replication dynamic equation of the strategy selection of the government regulator is as follows:

$$F(z) = \frac{dz}{dt} = z(E_{31} - \overline{E_3}) = z(1-z)(E_{31} - E_{32}) \\ = z(z-1)\begin{bmatrix} C_{gh} - C_{gl} - E_g - F_c - F_{\mathrm{m}} + \mathrm{x}(E_g + F_c + J_c) \\ +\mathrm{y}(E_g + F_{\mathrm{m}} + J_m) - \mathrm{xy}E_g \end{bmatrix} \tag{18}$$

The first-order derivatives of z and set $I(y)$ are the following:

$$\frac{d(F(z))}{dz} = (2y-1)\begin{bmatrix} C_{gh} - C_{gl} - E_g - F_c - F_{\mathrm{m}} + \mathrm{x}(E_g + F_c + J_c) \\ +\mathrm{y}(E_g + F_{\mathrm{m}} + J_m) - \mathrm{xy}E_g \end{bmatrix} \tag{19}$$

Set

$$I(y) = C_{gh} - C_{gl} - E_g - F_c - F_{\mathrm{m}} + \mathrm{x}(E_g + F_c + J_c) + \mathrm{y}(E_g + F_{\mathrm{m}} + J_m) - \mathrm{xy}E_g \tag{20}$$

When $y = \frac{[C_{gh} - C_{gl} - E_g - F_c - F_{\mathrm{m}} + \mathrm{x}(E_g + F_c + J_c)]}{(xE_g - E_g - F_{\mathrm{m}} - J_m)} = y^{**}$, $I(y) = 0$, and $F(z) = 0$. Thus, all values of z are in an evolutionary steady state.

According to the stability theorem of the differential equation, the probability that the government regulator will select strict regulation is in a stable state that must satisfy $F(z) = 0$ and $\frac{d(F(z))}{dz} < 0$. Since $\frac{\partial I(y)}{\partial y} < 0$, $I(y)$ is a decreasing function with respect to y. Therefore, when $y < y^{**}$, $I(y) > 0$. When $\frac{d(F(z))}{dz|_{z=1}} < 0$ and $F(z)|_{z=1} = 0$, at this time, $z = 1$ is the ESS of the government regulator. Similarly, when $y > y^{**}$, we obtain $z = 0$ as the ESS. Assume a three-dimensional space: $M = \{D(x, y, z) | 0 \le x \le 1, 0 \le y \le 1, 0 \le z \le 1\}$. When the initial state of the game lies within space V_{C_1}, the government regulator will eventually evolve to carry out loose regulation. When the initial state of the game lies within space V_{C_2}, the government regulator will eventually evolve in carrying out strict regulation. Based on the above analysis process, the evolutionary phase diagram of the strategy of the government regulator is drawn, as shown in Figure 4.

Corollary 5. The probability of strict supervision by the government regulator is positively correlated with the fines imposed by the regulator on the EPC general contractor and supervisory unit and the penalties imposed by higher authorities for loose regulation by the regulator, and it is negatively correlated with the cost difference between the strict and loose regulation of the EPC general contractor and supervisory unit by the regulator.

Proof. The first-order partial derivatives of each element are found separately for V_{C_2}, $\frac{\partial V_{C_2}}{\partial(E_g)} > 0$, $\frac{\partial V_{C_2}}{\partial(F_c)} > 0$, $\frac{\partial V_{C_2}}{\partial(F_m)} > 0$, $\frac{\partial V_{C_2}}{\partial(C_{gh} - C_{gl})} < 0$, $\frac{\partial V_{C_2}}{\partial(J_c)} < 0$, and $\frac{\partial V_{C_2}}{\partial(J_m)} < 0$. Therefore, any increase in E_g, F_c, or F_{m} or decrease in $(C_{gh} - C_{gl})$, J_c, J_m can increase the probability of strict regulation by the government regulator.

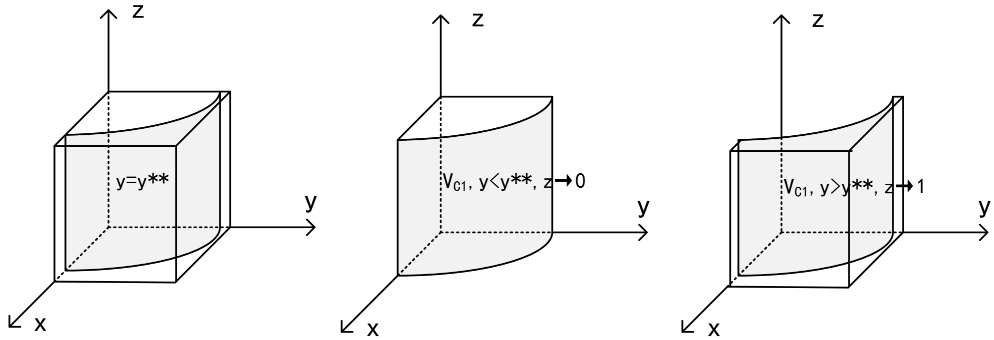

Figure 3. The evolutionary phase diagram of the strategy of the government regulator.

Corollary 5 shows that when the fine set by higher authorities is higher, this will motivate the government regulator more to fulfill its own duty to enforce strict regulation. When the punishment of the government regulator for nonstandard construction and loose supervision is higher, the rate of strict supervision by the government regulator is higher. Correspondingly, when the government regulator is paid more for building to the specifications and for strict supervision, the financial burden on the government regulator will be increased, and the rate of strict supervision by the government regulator will be reduced. This phenomenon suggests that the amount of incentive subsidies and penalties offered by government regulators should be set at a reasonable level to motivate regulators to adopt a strict regulatory strategy.

Corollary 6. The probability of strict supervision by the government regulator increases with the decrease in the probability of the EPC general contractor building according to the specifications or the probability of strict supervision by the supervisory unit.

Proof. The analysis of the stability of the government regulator's strategy shows that when $y < \frac{[C_{gh}-C_{gl}-E_g-F_c-F_{\mathrm{m}}+x(E_g+F_c+J_c)]}{(xE_g-E_g-F_{\mathrm{m}}-J_m)}$ or $x < \frac{[y(-E_g-F_{\mathrm{m}}-J_m)-(C_{gh}-C_{gl}-E_g-F_c-F_{\mathrm{m}})]}{(E_g+F_c+J_c-yE_g)}$, $I(y) > 0$. At this point, $\frac{d(F(z))}{dz|_{z=1}} < 0$, and $F(z)|_{z=1} = 0$. Thus, $y = 0$ is the ESS of the government regulator. Similarly, when $y > \frac{[C_{gh}-C_{gl}-E_g-F_c-F_{\mathrm{m}}+x(E_g+F_c+J_c)]}{(xE_g-E_g-F_{\mathrm{m}}-J_m)}$ or $x > \frac{[y(-E_g-F_{\mathrm{m}}-J_m)-(C_{gh}-C_{gl}-E_g-F_c-F_{\mathrm{m}})]}{(E_g+F_c+J_c-yE_g)}$, $I(y) < 0$. At this point, $\frac{d(F(z))}{dz|_{z=0}} < 0$, and $F(z)|_{z=0} = 0$. Thus, $z = 0$ is the ESS of the government regulator. Therefore, with the gradual decrease in x and y, the stable strategy of the government regulator increases from $z = 0$ (loose regulation) to $z = 1$ (strict regulation).

Corollary 6 shows that the rate of strict supervision by the government regulator is influenced by the choice of strategy of the EPC general contractor and supervisory unit. When the EPC general contractor does not build according to the specifications or the supervisory unit conducts loose supervision, these behaviors will prompt the government regulator to adopt a stable strategy of strict regulation.

4.4 Stability Analysis of The Equilibrium Point of The Tripartite Evolutionary Game System

Based on the stability analysis of the strategies of the EPC general contractor, supervisory unit and government regulator, a holistic analysis of the tripartite system is conducted. From $F(x) = 0, F(y) = 0, F(z) = 0$, we obtain the system equilibrium points of $E_1(0,0,0)$,$E_2(1,0,0)$,$E_3(0,1,0)$,$E_4(0,0,1)$,$E_5(1,1,0)$,$E_6(1,0,1)$,$E_7(0,1,1)$,$E_8(1,1,1)$,

$$E_9\left(-\frac{(C_{ml}-C_{mh}-B_b+F_m+J_m+T_m)}{(B_b+C_{mh}-C_{ml})}, \frac{(B_b+C_{cb}-C_{cg}+F_c+J_c+T_c)}{(B_b-R_c)}, 1\right),$$

$$E_{10}\left(1, -\frac{(C_{gh}-C_{gl}-F_m+J_c)}{(F_m+J_m)}, -\frac{(C_{ml}-C_{mh}+T_m)}{(C_{mh}-C_{ml}+F_m+J_m)}\right),$$

$$E_{11}\left(0, \frac{(C_{gl}-C_{gh}+E_g+F_c+F_m)}{(E_g+F_m+J_m)}, \frac{(B_b+C_{mh}-C_{ml}-T_m)}{(F_m+J_m)}\right),$$

$$E_{12}\left(-\frac{(C_{gh}-C_{gl}-F_c+J_m)}{(F_c+J_c)}, 1, -\frac{(C_{cb}-C_{cg}+R_c+T_c)}{(F_c+J_c)}\right),$$

$$E_{13}\left(\frac{(C_{gl}-C_{gh}+E_g+F_c+F_m)}{(E_g+F_c+J_c)}, 0, -\frac{(B_b+C_{cb}-C_{cg}+T_c)}{(F_c+J_c)}\right)$$ and

$E_{14}\left(\frac{(B_b+C_{mh}-C_{ml}-T_m)}{B_b},\frac{(B_b+C_{cb}-C_{cg}+T_c)}{(B_b-R_c)},0\right)$.

E_1, E_2, E_3, E_4, E_5, E_6, E_7, and E_8 form the boundary of the equilibrium solution domain of the evolutionary game, and the enclosed region $M=\{(x,y,z)|0\le x\le 1,0\le y\le 1,0\le z\le 1\}$ is the equilibrium solution domain of the tripartite evolutionary game. In the replicated dynamic system that consists of the EPC general contractor, supervisory unit and government regulator, $E_9, E_{10}, E_{11}, E_{11}, E_{12}, E_{13}, E_{14}$ are nonasymptotic steady states. Therefore, only the asymptotic stability of E_1, E_2, E_3, E_4, E_5, E_6, E_7, and E_8 must be discussed.

The Jacobi matrix of the dynamically evolving replicated dynamic system of the EPC general contractor, supervisory unit and regulatory department is as follows:

$$J=\begin{bmatrix}\frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} & \frac{\partial F(x)}{\partial z}\\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} & \frac{\partial F(y)}{\partial z}\\ \frac{\partial F(z)}{\partial x} & \frac{\partial F(z)}{\partial y} & \frac{\partial F(z)}{\partial z}\end{bmatrix}=\begin{bmatrix}J_1 & J_2 & J_3\\ J_4 & J_5 & J_6\\ J_7 & J_8 & J_9\end{bmatrix} \tag{21}$$

$$J_1=(2x-1)\left[C_{cg}-C_{cb}-B_b-T_c+y(B_b-R_c)-z(F_c+J_c)\right] \tag{22}$$
$$J_2=x(x-1)[B_b-R_c] \tag{23}$$
$$J_3=x(x-1)[-F_c-J_c] \tag{24}$$
$$J_4=y(y-1)[B_b-z(C_{mh}-C_{ml})] \tag{25}$$
$$J_5=(2y-1)[C_{mh}+B_b-C_{ml}-T_m-xB_b-z(F_\mathrm{m}+J_m)-xz(C_{mh}-C_{ml})] \tag{26}$$
$$J_6=y(y-1)[-(F_\mathrm{m}+J_m)-x(C_{mh}-C_{ml})] \tag{27}$$
$$J_7=z(z-1)\left[\left(E_g+F_c+J_c\right)-\mathrm{y}E_g\right] \tag{28}$$
$$J_8=z(z-1)\left[\left(E_g+F_\mathrm{m}+J_m\right)-xE_g\right] \tag{29}$$
$$J_9=(2z-1)\begin{bmatrix}C_{gh}-C_{gl}-E_g-F_c-F_\mathrm{m}+x\left(E_g+F_c+J_c\right)\\ +\mathrm{y}\left(E_g+F_\mathrm{m}+J_m\right)-x\mathrm{y}E_g\end{bmatrix} \tag{30}$$

Equilibrium point $E_1(0,0,0)$ replicates the Jacobi matrix of the dynamic system as follows:

$$J_1=\begin{bmatrix}B_b+C_{cb}-C_{cg}+T_c & 0 & 0\\ 0 & C_{ml}-C_{mh}-B_b+T_m & 0\\ 0 & 0 & C_{gl}-C_{gh}+E_g+F_c+F_m\end{bmatrix} \tag{31}$$

It can be derived that the equilibrium point $E_1(0,0,0)$ replicates the eigenvalues of the Jacobi matrix J_1 of the dynamic system. $\lambda_1=B_b+C_{cb}-C_{cg}+T_c$; $\lambda_2=C_{ml}-C_{mh}-B_b+T_m$; and $\lambda_3=C_{gl}-C_{gh}+E_g+F_c+F_m$. Similarly, the remaining eight equilibrium points of the replicated dynamic system are brought into the Jacobi matrix equation. The obtained eigenvalues of the equilibrium points are shown in Table 2.

Table 2. Eigenvalues of equilibrium points

Equilibrium points	Jacobi matrix eigenvalues		Stability conclusion	Conditions
	λ_1, λ_2, λ_3	Real part symbol		
$E_1(0,0,0)$	$B_b+C_{cb}-C_{cg}+T_c$,$C_{ml}-C_{mh}-B_b+T_m$,$C_{gl}-C_{gh}+E_g+F_c+F_m$	$(-,-,?)$	ESS	A
$E_2(1,0,0)$	$C_{ml}-C_{mh}+T_m$,$C_{cg}-C_{cb}-B_b-T_c$,$C_{gl}-C_{gh}+F_m-J_c$	$(-,+,?)$	Unstable	/
$E_3(0,1,0)$	$C_{cb}-C_{cg}+R_c+T_c$,$C_{gl}-C_{gh}+F_c-J_m$,$B_b+C_{mh}-C_{ml}-T_m$	$(+,?,?)$	Unstable	/
$E_4(0,0,1)$	$C_{gh}-C_{gl}-E_g-F_c-F_m$,$B_b+C_{cb}-C_{cg}+F_c+J_c+T_c$,$C_{ml}-C_{mh}-B_b+F_m+J_m+T_m$	$(?,?,?)$	ESS	B
$E_5(1,1,0)$	$C_{mh}-C_{ml}-T_m$,$C_{gl}-C_{gh}-J_c-J_m$,$C_{cg}-C_{cb}-R_c-T_c$	$(?,-,-)$	ESS	C

Equilibrium points	Jacobi matrix eigenvalues		Stability conclusion	Conditions
	λ_1, λ_2, λ_3	Real part symbol		
$E_6(1,0,1)$	$F_m+J_m+T_m$,$C_{gh}-C_{gl}-F_m+J_c$,$C_{cg}-C_{cb}-B_b-F_c-J_c-T_c$	$(+,?,?)$	Unstable	/
$E_7(0,1,1)$	$C_{gh}-C_{gl}-F_c+J_m$,$C_{cb}-C_{cg}+F_c+J_c+R_c+T_c$,$B_b+C_{mh}-C_{ml}-F_m-J_m-T_m$	$(?,+,?)$	Unstable	/
$E_8(1,1,1)$	$-F_m-J_m-T_m$,$C_{gh}-C_{gl}+J_c+J_m$,$C_{cg}-C_{cb}-F_c-J_c-R_c-T_c$	$(-,+,-)$	Unstable	/
A: $C_{gh}-C_{gl}>E_g+F_c+F_m$; B: $C_{gh}-C_{gl}<E_g+F_c+F_m$; $C_{cg}-C_{cb}>B_b+F_c+J_c+T_c$; $C_{mh}-C_{ml}+B_b>F_m+J_m+T_m$ C: $C_{mh}<C_{ml}+T_m$				

Corollary 7. When $C_{gh}-C_{gl}>E_g+F_c+F_m$, a stable point $E_1(0,0,0)$ exists of the replicated dynamic system.

Proof. According to Table 2, the eigenvalues of the Jacobi matrix that correspond to $E_1(0,0,0)$ are nonpositive when condition A is satisfied, and in this case, $E_1(0,0,0)$ is the ESS.

Corollary 7 shows that when the cost difference between strict and loose regulation by the government regulator is greater than the benefit of the fines obtained from strict regulation and the fines imposed by higher authorities are lower, the government regulator will adopt the strategy of loose regulation. According to the different initial points chosen by the three parties' strategies (the EPC general contractor does not build according to the specifications, the supervisory unit carries out loose supervision, and the government regulator carries out loose regulation), the subset of strategies is the evolutionary stable point of the three-dimensional dynamic system. At this time, the government regulator lacks effectiveness and cannot effectively constrain the behavior of the EPC general contractor and supervisory unit. The risks to prefabricated construction quality and safety, people's lives and the safety of property are great, which produces a serious threat. To avoid this combination of stable strategies, the government regulator should set a sufficiently high fine amount, or higher authorities should set a sufficiently high fine to exert the effect of the governmental reward and punishment mechanism.

Corollary 8. When $C_{gh}-C_{gl}<E_g+F_c+F_m$, $C_{cg}-C_{cb}>B_b+F_c+J_c+T_c$, and $C_{mh}-C_{ml}+B_b>F_m+J_m+T_m$, a stable point $E_4(0,0,1)$ exists of the replicated dynamic system.

Proof. According to Table 2, the eigenvalues of the Jacobi matrix that correspond to $E_1(0,0,0)$ are nonpositive when condition B is satisfied, and in this case, $E_4(0,0,1)$ is the ESS.

Corollary 8 shows that when the cost difference between strict and loose regulation by the government regulator is less than the benefit of the fines obtained from strict regulation and the fines imposed by higher authorities are higher, the government regulator will adopt the strategy of strict regulation. When the cost difference between the EPC general contractor building according to the specifications and not building according to the specifications is greater than the sum of the EPC general contractor's rent-seeking costs, speculative costs, and government regulatory rewards and penalties for the EPC general contractor, the contractor will adopt a strategy of not building according to the specifications. When the cost difference between strict supervision and loose supervision by the supervisory unit plus the benefits of engaging in rent-seeking are greater than the cost of speculation of the supervisory unit and the sum of the rewards and penalties of the government regulator, the supervisory unit will adopt a loose supervision strategy. According to the different initial points chosen by the three parties' strategies (the EPC general contractor does not build according to the specifications, the supervisory unit carries out loose supervision, and the government regulator carries out strict regulation), the subset of strategies is the evolutionary stable point of the replicated dynamic system. The sum of rewards and punishments from the government regulator to the EPC general contractor and supervisory unit should be higher than their speculative gains to effectively prevent the emergence of this stable strategy combination. Therefore, the reasonable setting of the reward and punishment mechanism for each unit by the supervisory unit can guarantee the quality and safety of prefabricated buildings.

Corollary 9. When $C_{mh}<C_{ml}+T_m$, a stable point $E_5(1,1,0)$ exists of the replicated dynamic system.

Proof. According to Table 2, the eigenvalues of the Jacobi matrix that correspond to $E_5(1,1,0)$ are nonpositive when condition C is satisfied, and in this case, $E_5(1,1,0)$ is the ESS.

Corollary 9 shows that when the cost of strict supervision is less than the sum of the cost of loose supervision and the cost of speculation of the supervisory unit, the government regulator will adopt the strategy of loose regulation. According to the different initial points chosen by the three parties' strategies (the EPC general contractor builds according to the specifications, the supervisory unit carries out strict supervision, and the government regulator carries out loose regulation), the subset of strategies is the evolutionary stable point of the three-dimensional dynamic system. At this time, the cost of speculation is high, the EPC general contractor and supervisory unit will tend to choose the strategy of building according to the specifications and carrying out strict supervision, and the lack of effectiveness of the government regulator will be unable to effectively restrain the behavior of the EPC general contractor and supervisory unit.

5. SIMULATION ANALYSIS

To verify the validity of the evolutionary stability analysis, numerical simulations were performed by using MATLAB 2017b in conjunction with realistic situations. Array 1 is as follows: $R_c = 160$，$C_{cg} = 140$，$C_{cb} = 90$，$B_b = 20$，$T_c + T_m = 10$，$R_m = 40$，$C_{mh} = 30$，$C_{ml} = 20$，$C_{gh} = 30$，$C_{gl} = 15$，$F_c + F_m = 15$，$J_c + J_m = 10$，$R_g = 10$，$D_g = 10$，$E_g = 10$. The conditions in Corollary 8 are satisfied, and based on this, the influence of the main parameter values, different initial intentions in the evolutionary process and the results of the participating subjects are analyzed.

First, we analyze the influence of the intensity of government rewards and punishments on the evolutionary process and the results of the participating subjects. The other parameters are kept constant based on array 1, and values $F_c + F_m = 0$，15，30 are assigned. The simulation results of the replicated dynamic system evolving 50 times are shown in Figure 5. We keep the other parameters unchanged based on array 1 and assign $J_c + J_m = 10$，20，30. The simulation results of the replicated dynamic system evolving 50 times are shown in Figure 6.

As shown in Figure 5, when $F_c + F_m = 0$, condition A is satisfied at this time, and the ESS of the replicated dynamic system is $(0,0,0)$. When $F_c + F_m = 15$，30, the ESS of the replicated dynamic system is $(0,0,1)$. The simulation results show that the system tends to evolve toward the stationary point during replicator dynamics. When the penalty amount set by higher authorities is small, and condition A is satisfied, the government regulator will tend to choose the strategy of loose regulation because the penalty amount is too low. When the penalty amount satisfies condition B, the government regulator will tend to choose the strict regulation strategy, and as the penalty amount gradually increases, the convergence time for the government regulator to choose the strict regulation strategy decreases. Therefore, setting reasonable penalty amounts and increasing the penalties for irregularities by the EPC general contractor and the supervisory unit can help improve the probability of active supervision by the government regulator.

As shown in Figure 6, when $J_c + J_m = 10$，20，30, the ESS of the replicated dynamic system is $(0,0,1)$. The simulation results show that the system tends to evolve toward the stationary point during replicator dynamics, the decrease in the amount of incentives from the government regulator to the EPC general contractor and supervisory unit can accelerate the evolution of the government regulator choosing strict regulation, and the probability of strict government regulation increases as $J_c + J_m$ decreases.

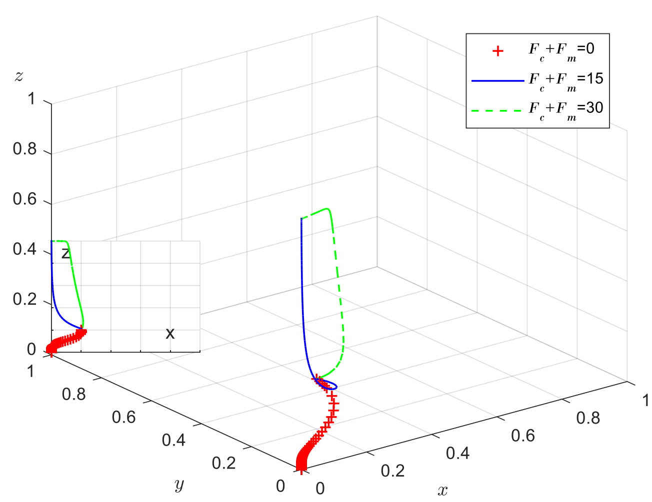

Figure 4. The influence of government regulator penalties.

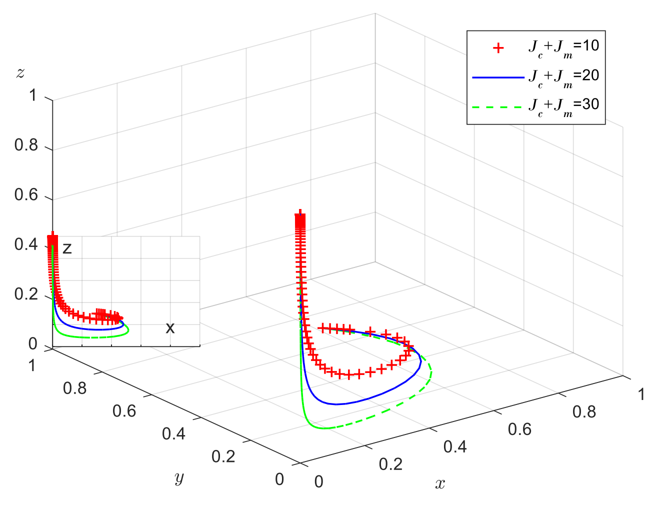

Figure 5. The influence of government regulator incentives.

Second, we analyze the influence of fines by higher authorities on the evolutionary process and the results of the participating subjects. The other parameters are kept constant based on array 1 and v $E_g = 10$，20，30 are assigned. The simulation results of the replicated dynamic system evolving 50 times are shown in Figure 7. The figure clearly shows that an increase in E_g increases the probability of strict government regulation during the evolutionary process. Therefore, the imposition of severe administrative penalties by higher authorities can make the regulatory authorities maintain a high probability of strict supervision, increase the probability of standardized construction and strict supervision, and further reduce the quality problems of prefabricated buildings.

Finally, we analyze the influence of speculative costs on the evolutionary process and the results of the participating subjects. We keep the other parameters unchanged based on array 1 and assign $T_c + T_m = 10$，20，40. The simulation results of the replicated dynamic system evolving 50 times are shown in Figure 8. When $T_c + T_m = 10$，20, condition B is satisfied, and at this time, the ESS of the replicated dynamic system is $(0,0,1)$. When $T_c + T_m = 30$, the ESS of the replicated dynamic system is $(1,1,0)$. The simulation results show that in the process of replicating the dynamic system tending toward the stability point when the speculative cost is small to satisfy condition B, the EPC general contractor and supervisory unit will tend to choose the strategy of not building according to the specifications and carrying out loose supervision because the speculative cost of the EPC general contractor and supervisory unit is too low. When the speculative cost satisfies condition C, the EPC general contractor and supervisory unit will tend to choose the strategy of the building according to the specifications and carrying out strict supervision. Therefore, the government regulator can promote the delivery and application of the digital results of the entire process of prefabricated buildings by accelerating the integrated application of BIM technology in the whole life cycle of the project, which improves the interaction and safety standards of construction data and strengthens the digital synergy of each construction process through information technology. It is necessary to undertake a pilot construction of the internet platform for the construction industry, build a government regulatory platform, and increase the cost of corporate speculation to thus improve the quality of prefabricated buildings.

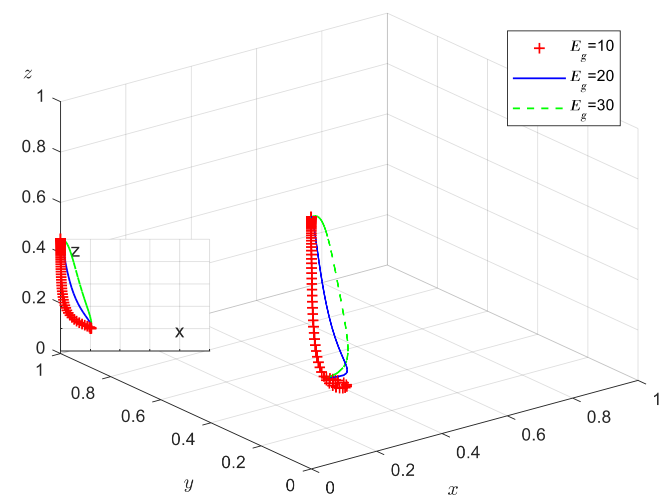

Figure 6. The influence of the higher authorities in charge on the punishment of the government regulator.

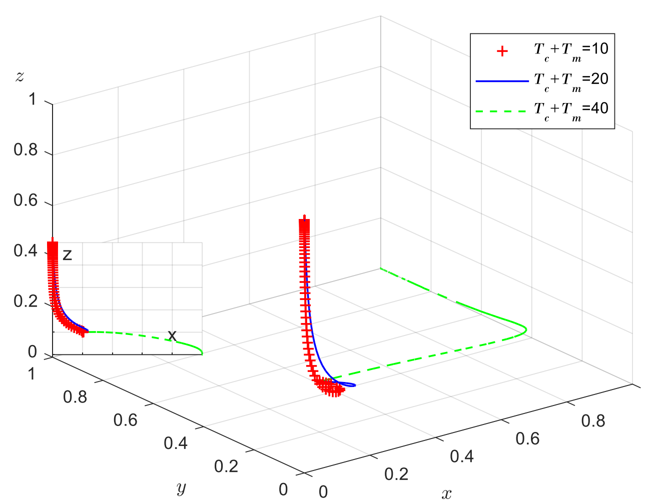

Figure 7. The influence of speculative costs.

Array 1 satisfies condition A. Array 2 is assigned as follows:

$R_c = 160$，$C_{cg} = 140$，$C_{cb} = 90$，$B_b = 20$，$T_c + T_m = 10$，$R_m = 40$，$C_{mh} = 30$，$C_{ml} = 20$，$C_{gh} = 60$，$C_{gl} = 15$，$F_c + F_m = 15$，$J_c + J_m = 10$，$R_g = 10$，$R_g = 10$，$D_g = 10$，$E_g = 10$.

Thus, condition B is satisfied. Array 3 is assigned as follows:

$R_c = 160$，$C_{cg} = 140$，$C_{cb} = 90$，$B_b = 20$，$T_c + T_m = 40$，$R_m = 40$，$C_{mh} = 30$，$C_{ml} = 20$，$C_{gh} = 60$，$C_{gl} = 15$，$F_c + F_m = 15$，$J_c + J_m = 10$，$R_g = 10$，$R_g = 10$，$D_g = 10$，$E_g = 10$.

Thus, condition C is satisfied. Arrays 1, 2, and 3 are evolved 50 times based on different initial strategy combinations, and the results are shown in Figures 9, 10, and 11, respectively.

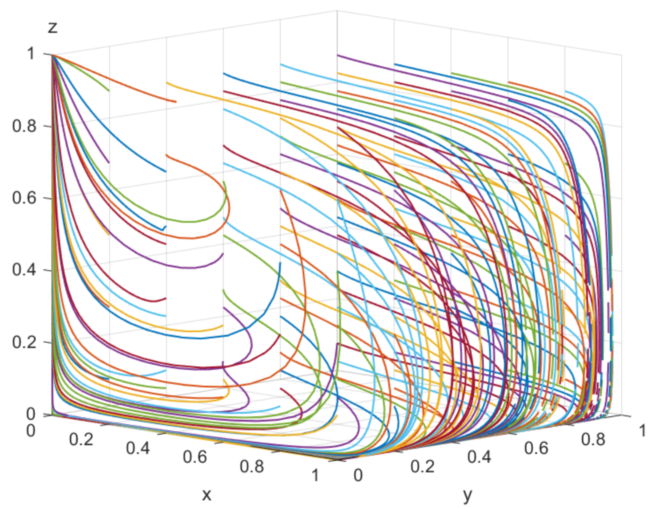

Figure 8. The results of evolving array 1 50 times based on different starting points.

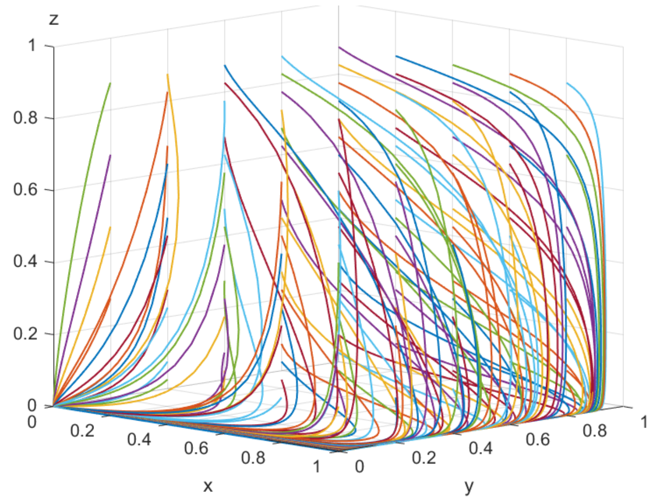

Figure 9. The results of evolving array 2 50 times based on different starting points.

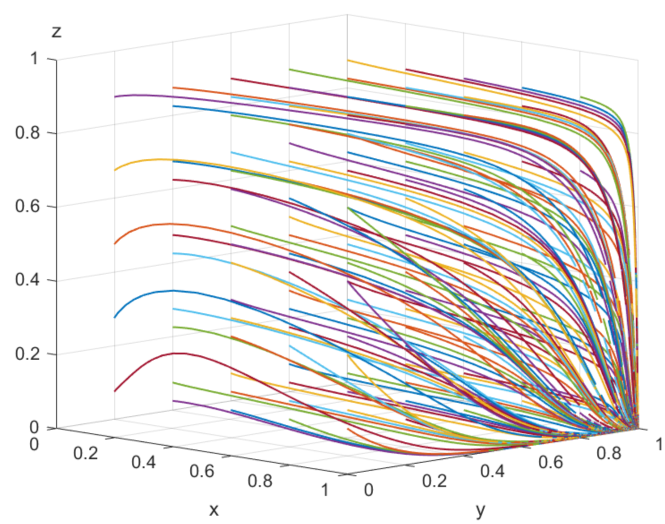

Figure 10. The result of evolving array 3 50 times based on different starting points.

As shown in Figure 9, array 1 is evolved 50 times based on different strategy starting points while assuming that condition B is satisfied. As a result, an evolutionary stable point $(0,0,1)$ exists, at which time the system exists as an evolutionary stability strategy combination (not built according to the specifications, loose supervision, and strict regulation), which is consistent with the conclusion of Corollary 8. Figure 10 shows that an evolutionary stable point $(0,0,0)$ exists by evolving array 2 50 times based on different strategy starting points while assuming that condition A is satisfied. An ESS combination (not built according to the specifications, loose supervision, and loose regulation) exists for the system, which is consistent with the conclusion of Corollary 7. Figure 11 shows that an evolutionary stable point $(1,1,0)$ exists by evolving array 3 50 times based on different strategy starting points while assuming that condition C is satisfied. An ESS combination for the system exists (built according to the specifications, strict supervision, and loose regulation), which is consistent with the conclusion of Corollary 9. Therefore, government regulators should examine the interests of EPC general contractors and supervisory units for prefabricated buildings from multiple perspectives, strengthen construction information technology, increase the cost of speculation, and ensure that the rewards and punishments for all parties are higher than the speculative gains to avoid prefabricated buildings with quality and safety problems.

Based on actual research, actual data from a construction company and a construction supervision unit in Anhui Province were selected. The project duration was 468 days, with a total income of 30.679 million yuan and total costs of 27.102 million yuan for the construction company. The total income for the supervision unit was 564,000 yuan, with supervision costs of 351,000 yuan. The penalty for noncompliance with regulations for both companies was set at 200,000 yuan, and the reward for standardized construction and supervision was set at 50,000 yuan. Based on the research, hidden costs such as speculation were estimated at 200,000 yuan, and regulatory costs were estimated at 100,000 yuan. The data were then evolved starting from three different strategies, i.e., (0.2 0.2 0.2), (0.5 0.5 0.5), (0.7 0.7 0.7), as shown in Figure 12. The final ESS is (1,1,0), which is consistent with the conclusion of Corollary 9. The simulation analysis is consistent with the inferred results and provides practical guidance for the quality regulation of prefabricated buildings.

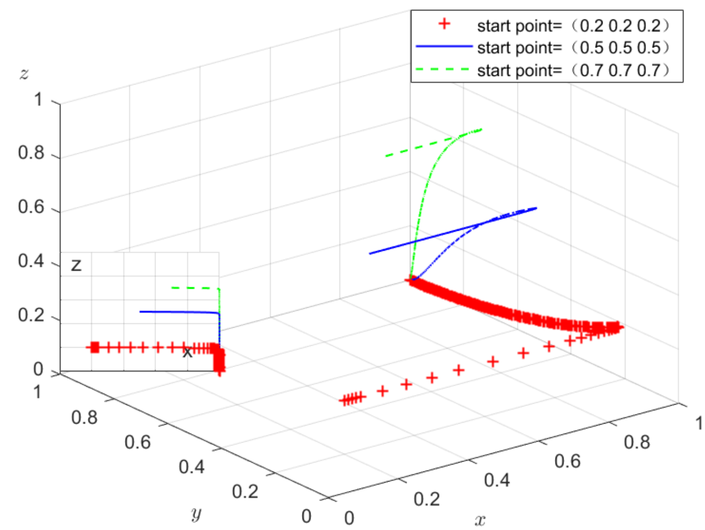

Figure 11. The result of the evolution of real-life data from three different starting points.

6. CONCLUSION

This paper constructs a tripartite evolutionary game model of the government, EPC general contractors, and supervision units. Furthermore, it analyzes the stability of the players' strategy choice, the stability of the equilibrium strategy combination in the game system and the relationship between the parameters. In addition, it verifies the validity of the inferred results through a numerical simulation analysis. Based on the relationships between different parameters and stability conditions, relevant comments and suggestions for government regulators are made, and the main conclusions obtained are as follows.

(1) A reasonable reward and punishment mechanism can effectively promote strict construction by general contractors and standardize the behavior of supervision units. Government regulators increase the incentives and penalties to help EPC general contractors and supervisory units build according to the specifications and conduct strict supervision. However, government regulators should also pay attention to the amount of subsidies. The increase in incentives will reduce the probability of strict regulation by the government, which is not conducive to the government's performance of its regulatory duties.

(2) The lower the speculative cost is, the higher the probability of general contractors and supervision units choosing rent-seeking behavior, which is not conducive to the government's regulation of the quality of prefabricated buildings. The sum of rewards and punishments for EPC general contractors and supervisory units should be higher than their speculative gains so that raising the speculative costs of EPC general contractors and supervisory units can also effectively improve the quality of prefabricated buildings.

(3) The severity of penalties imposed by higher authorities will affect the regulatory decisions of government regulators. The higher authorities increase the punishment for lack of regulation, which can also prompt government regulators to regularly carry out strict supervision and thus improve the quality of prefabricated buildings.

This paper reveals the evolutionary laws of the decision-making behaviors of EPC general contractors, supervisory units, and government regulators in the process of prefabricated building construction. In this way, it provides a theoretical reference and guidance for government departments on the quality supervision and healthy development of the prefabricated building industry. However, the following limitations still exist. Only the quality supervision of prefabricated buildings in the process of construction by EPC general contractors is considered, and the possible effects of design, production, and transportation on the quality of prefabricated buildings are not considered. The construction link of prefabricated buildings is the most important link that affects the quality of such buildings. Clarifying the evolutionary law of the decision-making behavior of the construction link also provides data support and a theoretical reference for research on the quality of the design, production, and transportation links in future research.

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