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Methods to Stimulate the Proactivity of Enterprises in Fulfilling Safety Responsibilities: A Fundamental Issue in Construction Safety Management

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Abstract: Management factors are among the most significant causes of construction safety incidents, and there is an issue of insufficient supervision at present. The degree of diligence exhibited by relevant entities is crucial, and the payoff can influence the decision-making behaviors of involved parties. Based on this, the aim of this paper is to investigate how to enhance the initiative of enterprises in fulfilling their safety responsibilities during the construction process. By developing a tripartite evolutionary game model that involves supervision companies, general contractors, and labor subcontractors and conducting numerical simulation analysis, we reveal that simultaneous proactive investment in safety by all three parties is challenging, with labor subcontractors being relatively more prone to opt for active safety investment. Supervision companies and general contractors often struggle to fulfill their safety duties at the same time. Factors such as the rewards and penalties stipulated in a contract, rent-seeking amounts, and accident-related losses have a significant impact on the evolution of the system. Based on the findings, we propose recommendations for construction management, which include the management of labor subcontracting in construction, the control of rent-seeking behaviors, and the establishment of a cooperative safety culture during the construction process.

Keywords: construction safety management; labor subcontracting; safety responsibility; evolutionary game; simulation analysis

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1. Introduction

The building sector ranks among the most significant and largest industries in numerous nations [1]. In spite of the importance that the construction industry has in both developing and developed countries by way of gross domestic product (GDP) and job opportunities, it has long been the industry most significantly responsible for high injury and fatality rates [2,3]. Among numerous fields, it is the construction sector that has experienced a significant number of workplace accidents and injuries [4]. Taking China's housing and municipal engineering as an example, the number of construction safety accidents has remained high for a long time, with a substantial number of fatalities each year [5]. Therefore, the situation of safety production in construction engineering is concerning in present day China, which is highly valued by both the government and the Party Central Committee in China [6].

Other scholars have explored the factors contributing to safety incidents. Among them, Bird [7] insisted that the root cause is defects in the management of relevant project participants. Zhang et al. [8] hold the opinion that management factors have a fundamental influence on the total safety performance and require systematic improvement. Pereira et al. [9] applied SEM to investigate the causal relationships between safety management system (SMS) factors and accident precursors. Additionally, a significant number of safety incident reports cite management factors as the cause [10]. Certainly, this also reflects a lack of due diligence in fulfilling the responsibilities of relevant entities [11,12].

The government has issued many policy documents to this end [13–15]. Therefore, management factors are of great importance, and the initiative of relevant entities in fulfilling their management responsibilities are also crucial.

To enhance the effectiveness of safety management, some scholars have made innovations from various perspectives, including safety training, safety assessment, the safety climate, and the safety culture. Li et al. [16] created a tailored virtual reality training method with individualized guidance to improve users' construction hazard inspection skills effectively. Luo et al. [17] developed a hybrid evaluation model to evaluate the construction safety risks of prefabricated subway stations. Al-Bayati et al. [18] presented a distinct and practical framework for the construction safety culture and climate, and then evaluated the perceived usability of it. Moreover, the application of safety technologies in construction site management is continuously advancing [19–21]. Undeniably, there has been significant progress in the technical level and in the management concepts of construction safety. However, the effectiveness of these achievements is based on the premise that the relevant enterprises are responsible and accountable, for they are, after all, the main entities responsible for construction safety [3,22]. Furthermore, the frequent mention of management-related causes in safety incident reports also clearly demonstrates that there are still instances where enterprises are not fully implementing their responsibilities. Therefore, it is essential to explore methods to enhance the enthusiasm and initiative of enterprise safety management from a fundamental perspective.

As a profit-oriented economic entity, a company is more likely to overlook the potential for safety incidents to occur and neglect long-term interests [23,24]. Accurately identifying the key stakeholders and studying the mechanisms of their interesting interactions is crucial [22,25]. The game theory addresses scenarios involving conflicts between rational agents and focuses on determining the optimal strategies for each individual to improve their expected outcomes [26]. With the advancement of models, the evolutionary game theory has emerged to compensate for the limitations of complete rationality and symmetric information in the traditional game theory, gaining gradual recognition and being applied to research on construction safety management [3,27].

In summary, it is critical to stimulate the initiative of enterprises to achieve safety management. The evolutionary game theory can predict and explain the behavioral strategies chosen by analyzing the payoffs of stakeholders under the assumption of bounded rationality. Therefore, the purpose of this paper is to explore effective methods to ensure that enterprises fulfill their safety responsibilities by establishing an evolutionary game model among stakeholders. We focus on addressing the following issues: (1) Who are the key stakeholders associated with safety responsibilities? (2) What are the payoff-related factors that influence the behavioral decisions of these stakeholders? (3) What are the evolutionary stable strategies of the game model? Which factors have a significant impact on the system's evolution? (4) Which set of evolutionary stable strategies is the most beneficial for construction safety? Through what measures can the system be guided more efficiently toward this set of strategies?

2. Literature Review

2.1. Application of Evolutionary Game Theory in Construction Safety Research

Currently, scholars are inclined to apply the evolutionary game theory to the analysis of safety behavior evolution. Huang et al. [25] constructed a two-sided evolutionary game model involving workers and managers, with the aim of investigating the evolutionary patterns of workers' unsafe behaviors and how to mitigate such behaviors. Wu et al. [3] develop an evolutionary game model to explore the safety behavior strategies of the main contractors and construction workers. Chen et al. [28] explored the stable state of construction safety supervision conducive to the sustainability of the construction industry through game analysis between contractors and regulators. Liu et al. [29] employed the evolutionary game theory to investigate how to incentivize the regulatory behavior of local governments and construction enterprises. Ning et al. [22] integrated the entity responsibility mechanism with the third-party participation mechanism and used an evolutionary game model to describe the decision-making interactions between the government and construction enterprises under these mechanisms. Jiang et al. [30] described and analyzed China's Construction Safety Supervision Mechanism (CSSM) from the perspective of the evolutionary game theory. Comprehensively, Guo et al. [31] conducted evolutionary game analysis from the perspective of safety education, focusing on the interactions among the government, construction units, and construction workers.

Additionally, as research progresses, issues such as the efficiency of safety management and resource allocation have also been incorporated into the scope of study. Zhang et al. [32] conducted evolutionary game analysis between government supervision departments and construction contractors to explore the methods for improving the safety supervision effectiveness of prefabricated construction projects. Su et al. [33] proposed the concept and framework of the Construction Safety Standard System (CSSS) and applied the evolutionary game theory to illustrate the decision-making processes involved in its establishment and application. Gong et al. [34] endeavored to propose an innovative approach for enhancing the efficacy of safety investment oversight and examine the decision-making dynamics among stakeholders within this proposed framework. Pi et al. [35] innovatively introduced the concept of a safety information system and used an evolutionary game model to validate the feasibility of this system. Peng et al. [36] combined the evolutionary game theory with genetic algorithms to diligently explore the effective allocation of safety resources.

Overall, the evolutionary game theory is primarily applied in research in two areas: the management of construction workers' safety behaviors and the management of regulatory behaviors involving the government, supervisors, and construction enterprises. However, the management of construction workers' safety behaviors is inherently intertwined with the oversight of the respective companies [3,24]. While the enhancement of safety management efficiency and the optimization of resource allocation are crucial to improving the safety performance, the active and positive collaboration of all the parties involved is still essential [33–35]. It is evident, therefore, that no matter the perspective of research, the initiative of a company to fulfill its responsibilities is fundamental. Given that the insufficient enforcement of responsibilities by relevant entities is a prominent and common issue in accident reports, the urgent task at hand remains to explore methods to enhance the proactiveness of corporate regulatory behavior [3,30].

2.2. Stakeholders Associated with Safety Responsibilities

Identifying the core stakeholders from construction companies and all the entities that could influence the due diligence of construction companies is essential. According to the literature reviewed in the previous section, the stakeholders in construction safety management primarily include the government, supervision entities, construction contractors, and construction workers. Firstly, although the government plays a significant role in policy making, safety supervision, and accident investigation, it often lacks an in-depth understanding of the specific details on construction sites. The hands-on work of safety management at a construction site is primarily carried out by the companies and front-line workers [20,37]. Secondly, while unsafe behavior on the part of workers is indeed a direct cause of safety incidents, it is also worth noting that the educational level of construction workers is generally low, and their awareness of safety is insufficient [38,39]. Given this context, when construction workers receive inadequate education, training, and on-site management, they struggle to recognize and address the various risks present in the construction industry [3,24,40]. Thus, we argue that supervision entities and construction contractors are the stakeholders most significantly associated with safety responsibilities.

In China's construction industry, the prevalent management hierarchy involves a three-level system that includes contractors, labor subcontractors, and workers [41]. Typically, construction entities outsource their contracted labor activities to qualified subcontractors. Subsequently, these labor subcontracting firms coordinate the workforce to execute the construction tasks and offer a technical direction [30,42]. It is obvious that labor subcontractors and contractors are two distinct entities, and subcontracting labor also involves the processes of bidding and contract signing. Therefore, there is also the presence of information asymmetry and conflicts of interest between the labor subcontractors and other entities [40,43]. However, in research on construction safety management, labor subcontractors have not received sufficient attention, which should have been studied as the key responsible entity for construction safety.

After reviewing the content from the previous section, we can summarize that the key stakeholders in construction safety management are supervision companies, general contractors, and labor subcontractors. This study employs the evolutionary game approach to investigate ways to enhance the proactive fulfillment of safety responsibilities by stakeholders. The main contributions of this paper are as follows: (1) Differentiate labor subcontractors from general contractors and fully consider the role of labor subcontractors in the process of safety management. (2) Comprehensively consider the interaction mechanisms among the internal entities of the system as well as the impact of external factors on the system. (3) Propose institutional suggestions for safety production from the perspective of government departments, combining the results of the game theory and simulation.

3. Methodology

3.1. Fundamental Assumptions

Supervision companies, general contractors, and labor subcontractors are the participants in this evolutionary game theory analysis. We referred to previous research to summarize the respective benefits for each party involved, as well as the benefits associated with their interactions. Firstly, these companies should make sufficient safety investments to ensure the safety of construction sites; however, in an attempt to increase profits, companies might reduce their safety investments [3,22,29]. When companies diligently fulfill their responsibilities, they can receive certain rewards [30]. Conversely, companies will face penalties, and in the event of a safety incident, they will also bear the corresponding accident-related losses [3,25,29]. In some cases, in order to evade regulation, general contractors might engage in rent-seeking behaviors towards supervision companies [30,44]. Based on this, in conjunction with the results of interviews with industry insiders, the following hypotheses are formulated as follows:

Assumption 1. *The supervision company is designated as Party 1, the general contractor is Party 2, and the labor subcontractor is Party 3. All three parties are considered to be boundedly rational agents, whose strategies are subject to adjustment over time, ultimately converging towards a stable strategy.*

Assumption 2. *The strategy space for the supervision companies is denoted as* $\alpha = (\alpha_1, \alpha_2) = (\text{Effective Supervision, Ineffective Supervision})$*, where the probability of effective supervision is x, and the probability of ineffective supervision is* $1 - x$*. The strategy space for the general contractor is denoted as* $\beta = (\beta_1, \beta_2) = (Proactive\ Management, Passive\ Management)$*, with the probability of proactive management being y, and the probability of passive management being* $1 - y$*. The strategy space for the labor subcontractor is denoted as* $\gamma = (\gamma_1, \gamma_2) = (Active\ Safety\ Investment, Passive\ Safety\ Investment)$*, where the probability of active safety investment is z, and the probability of Passive Safety Investment is* $1 - z$*,* $x, y, z \in [0, 1]$*.*

Assumption 3. *When the supervision company opts for effective supervision, the cost incurred for overseeing the safety management status of the contractor is denoted as* C_x*; choosing ineffective supervision can reduce this cost by* ΔC_x*. The general contractor incurs safety investment costs* C_y *for proactive management activities, such as safety production education and training, qualification review for labor companies and workers, and the identification of hazardous sources at a construction site. When adopting passive management, the firm can reduce these costs by* ΔC_y*. The labor subcontractor, under the premise of active safety investment, invests in activities, such as qualification review for workers, safety education and training, and the identification of safety hazards, incurring costs represented by* C_z *; with Passive Safety Investment, the labor company can reduce these costs by* ΔC_z*.*

Assumption 4. *When acting with passive management, the general contractor may attempt to seek rent from the supervision company. If the supervision company is also in a state of ineffective supervision, then the payment R will be accepted by the supervision company, and they will no longer strictly oversee the general contractor. In the absence of a safety incident, the general contractor can thus avoid default penalties.*

Assumption 5. *The supervision company, when it accurately addresses construction safety issues and makes significant contributions to safety management, can receive a reward denoted as A_1 from the construction employer ($A_1 < R$). The labor subcontractor, when it demonstrates a good safety performance, and the construction firm is proactively managed, can receive a reward denoted as A_2 from the general contractor ($A_2 < R$). If the supervision company provides effective supervision and the general contractor opts for passive management, the supervision company will report the situation to the construction employer, resulting in the general contractor bearing breach-of-contract compensation denoted as P_1. When the general contractor opts for proactive management and the labor subcontractor chooses a passive approach to safety investment, this can lead to potential safety hazards, for which the labor subcontractor will be liable to pay breach-of-contract compensation denoted as P_2.*

Assumption 6. *In the event that the aforementioned parties overlook safety issues and are lax in management, construction safety accidents are likely to occur. Let the direct and indirect losses caused by an accident be denoted as L. The probability of an accident occurring is represented as ω_i $(i = 0, 1, 2, 3)$, and "i" refers to the number of participants who have not fulfilled their safety responsibilities. We establish that $1 > \omega_3 > \omega_2 > \omega_1 > \omega_0 = 0$. In particular, when only the supervision company fails to fulfill its duties, the probability of an accident occurring is approximately 0. For the sake of convenience in calculation, we disregard the impact of different participants' irresponsibility on the probability when the value of "i" is the same.*

The parameters in the assumption part are sorted into Table 1.

Table 1. The parameters in the tripartite evolutionary game.

Parameters	Description
C_x	The investment of supervision company when opting for effective supervision
ΔC_x	The investment reduction in supervision company when adopting ineffective supervision
C_y	The investment of general contractor when opting for proactive management
ΔC_y	The investment reduction in general contractor when adopting passive management
C_z	The investment of labor subcontractor when opting for active safety investment
ΔC_z	The investment reduction in labor subcontractor when adopting Passive Safety Investment
A_1	Reward for supervision company paid by employer
A_2	Reward for labor subcontractor paid by general contractor
P_1	Penalties paid by general contractor to the employer
P_2	Penalties paid by labor subcontractor to the general contractor
L	Losses caused by safety accident
R	Rent-seeking costs paid by the general contractor to the supervision company
ω_i $(i = 0, 1, 2, 3)$	Probability of safety accident

3.2. Model Establishment

Drawing from the assumptions and parameter configurations, the evolutionary game payoff matrix can be derived, as presented in Table 2.

Table 2. Game payoff matrix.

General Contractor			Labor Subcontractor	
			Active Safety Investment z	**Passive Safety Investment** $1-z$
supervision company	Effective Supervision x	Proactive Management y	$-C_x$ $-C_y-A_2$ A_2-C_z	$-C_x$ $-C_y+P_2$ $-C_z+\Delta C_z-P_2-\omega_1 L$
		Passive Management $1-y$	A_1-C_x $-C_y+\Delta C_y-P_1-\omega_1 L$ $-C_z$	A_1-C_x $-C_y+\Delta C_y-P_1-\omega_2 L$ $-C_z+\Delta C_z-\omega_2 L$
	Ineffective Supervision $1-x$	Proactive Management y	$-C_x+\Delta C_x$ $-C_y-A_2$ A_2-C_z	$-C_x+\Delta C_x-\omega_2 L$ $-C_y+P_2$ $-C_z+\Delta C_z-P_2-\omega_2 L$
		Passive Management $1-y$	$R-C_x+\Delta C_x-\omega_2 L$ $-C_y+\Delta C_y-R-\omega_2 L$ $-C_z$	$R-C_x+\Delta C_x-\omega_3 L$ $-C_y+\Delta C_y-R-\omega_3 L$ $-C_z+\Delta C_z-\omega_3 L$

Assuming that the expected payoff for the supervision company when choosing the "effective supervision" strategy is denoted as E_{11}, and the expected payoff for the "Ineffective Supervision" strategy is E_{12}, with an average expected payoff E_1, then we have

$$E_{11}=yz(-C_x)+y(1-z)(-C_x)+(1-y)z(A_1-C_x)+(1-y)(1-z)(A_1-C_x) \tag{1}$$

$$\begin{aligned}E_{12}=&yz(-C_x+\Delta C_x)+y(1-z)(-C_x+\Delta C_x-\omega_2 L)+(1-y)z(R-C_x+\Delta C_x-\omega_2 L)\\&+(1-y)(1-z)(R-C_x+\Delta C_x-\omega_3 L)\end{aligned} \tag{2}$$

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

Assuming that the expected payoff for the general contractor when choosing the "Proactive Management" strategy is denoted as E_{21}, and the expected payoff for the "Passive Management" strategy is E_{22}, with an average expected payoff of E_2, then we have

$$E_{21}=xz(-C_y-A_2)+x(1-z)(-C_y+P_2)+(1-x)z(-C_y-A_2)+(1-x)(1-z)(-C_y+P_2) \tag{4}$$

$$\begin{aligned}E_{22}=&xz(-C_y+\Delta C_y-P_1-\omega_1 L)+x(1-z)(-C_y+\Delta C_y-P_1-\omega_2 L)\\&+(1-x)z(-C_y+\Delta C_y-R-\omega_2 L)+(1-x)(1-z)(-C_y+\Delta C_y-R-\omega_2 L)\end{aligned} \tag{5}$$

$$E_2=yE_{21}+(1-y)E_{22} \tag{6}$$

Assuming that the expected payoff for the labor subcontractor when choosing the "active safety investment" strategy is denoted as E_{31}, and the expected payoff for the "Passive Safety Investment" strategy is E_{32}, with an average expected payoff of E_3, then we have

$$E_{31}=xy(A_2-C_z)+x(1-y)(-C_z)+(1-x)y(A_2-C_z)+(1-x)(1-y)(-C_z) \tag{7}$$

$$\begin{aligned}E_{32}=&xy(-C_z+\Delta C_z-P_2-\omega_1 L)+x(1-y)(-C_z+\Delta C_z-\omega_2 L)\\&+(1-x)y(-C_z+\Delta C_z-P_2-\omega_2 L)+(1-x)(1-y)(-C_z+\Delta C_z-\omega_3 L)\end{aligned} \tag{8}$$

$$E_3=zE_{31}+(1-z)E_{32} \tag{9}$$

Through the presented analysis, the replication dynamics equations of the supervision companies, the general contractors, and the labor subcontractors are as follows:

$$F(x)=\frac{dx}{dt}=x(E_{11}-E_1) \tag{10}$$

$$F(y)=\frac{dy}{dt}=y(E_{21}-E_2) \tag{11}$$

$$F(z) = \frac{dz}{dt} = z(E_{31} - E_3) \tag{12}$$

3.3. Evolutionary Equilibrium and Stability Analysis

From $F(x) = 0, F(y) = 0, F(z) = 0$, the system's pure strategy equilibrium solutions are $E_1(0,0,0)$, $E_2(1,0,0)$, $E_3(0,1,0)$, $E_4(0,0,1)$, $E_5(1,1,0)$, $E_6(1,0,1)$, $E_7(0,1,1)$, and $E_8(1,1,1)$. We constructed the following Jacobian matrix of the system:

$$J = \begin{bmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} & \frac{\partial F(x)}{\partial z} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} & \frac{\partial F(y)}{\partial z} \\ \frac{\partial F(z)}{\partial x} & \frac{\partial F(z)}{\partial y} & \frac{\partial F(z)}{\partial z} \end{bmatrix} = \begin{bmatrix} A & B & C \\ D & E & F \\ G & H & I \end{bmatrix} \tag{13}$$

$$\text{A} = (1-2x)[A_1 - \Delta C_x - R + L\omega_3 + y(R - A_1 + L\omega_2 - L\omega_3) + yz(L\omega_3 - 2L\omega_2) + z(L\omega_2 - L\omega_3)] \tag{14}$$

$$\text{B} = x(1-x)[R - A_1 + L\omega_2 - L\omega_3 + z(L\omega_3 - 2L\omega_2)] \tag{15}$$

$$\text{C} = x(1-x)[L\omega_2 - L\omega_3 + y(L\omega_3 - 2L\omega_2)] \tag{16}$$

$$\text{D} = y(1-y)[P_1 - R + zL\omega_1 + (1-2z)L\omega_2 + (z-1)L\omega_3] \tag{17}$$

$$\text{E} = (1-2y)[P_2 - \Delta C_y + R + L\omega_3 + x(P_1 - R + L\omega_2 - L\omega_3) + z(L\omega_2 - L\omega_3 - A_2 - P_2) + xz(L\omega_1 - 2L\omega_2 + L\omega_3)] \tag{18}$$

$$\text{F} = y(1-y)[xL\omega_1 + (1-2x)L\omega_2 + (x-1)L\omega_3 - A_2 - P_2] \tag{19}$$

$$\text{G} = z(1-z)[yL\omega_1 + (1-2y)L\omega_2 + (y-1)L\omega_3] \tag{20}$$

$$\text{H} = z(1-z)[A_2 + P_2 + xL\omega_1 + (1-2x)L\omega_2 + (x-1)L\omega_3] \tag{21}$$

$$\text{I} = (1-2z)[L\omega_3 - \Delta C_z + x(L\omega_2 - L\omega_3) + y(A_2 + P_2 + L\omega_2 - L\omega_3) + xy(L\omega_1 - 2L\omega_2 + L\omega_3)] \tag{22}$$

According to the first method of Lyapunov, if all the eigenvalues of the Jacobian matrix have negative real parts, then the equilibrium point is asymptotically stable. We substituted the x, y, z values of the pure strategy solutions $E_1 \sim E_8$ into the Jacobian matrix to obtain the eigenvalues for points $E_1 \sim E_8$, as shown in Table 3, where the symbol "+" denotes a positive eigenvalue, the symbol "-" denotes a negative eigenvalue, and the symbol "×" denotes an eigenvalue with an uncertain sign.

Table 3. The characteristic values of the pure strategy equilibrium points.

Equilibrium Points	Eigenvalues of the Jacobian Matrix			Feature Value Symbol	Stability
	λ_1	λ_2	λ_3		
$E_1(0,0,0)$	$L\omega_3 - \Delta C_z$	$A_1 - \Delta C_x - R + L\omega_3$	$P_2 - \Delta C_y + R + L\omega_3$	+ + +	Unstable point
$E_2(1,0,0)$	$L\omega_2 - \Delta C_z$	$\Delta C_x - A_1 + R - L\omega_3$	$P_1 - \Delta C_y + P_2 + L\omega_2$	× - +	Unstable point
$E_3(0,1,0)$	$L\omega_2 - \Delta C_x$	$\Delta C_y - P_2 - R - L\omega_3$	$A_2 - \Delta C_z + P_2 + L\omega_2$	× - +	Unstable point
$E_4(0,0,1)$	$\Delta C_z - L\omega_3$	$A_1 - \Delta C_x - R + L\omega_2$	$R - \Delta C_y - A_2 + L\omega_2$	- × ×	To be discussed
$E_5(1,1,0)$	$\Delta C_x - L\omega_2$	$\Delta C_y - P_1 - P_2 - L\omega_2$	$A_2 - \Delta C_z + P_2 + L\omega_1$	× - ×	To be discussed
$E_6(1,0,1)$	$\Delta C_z - L\omega_2$	$P_1 - \Delta C_y - A_2 + L\omega_1$	$\Delta C_x - A_1 + R - L\omega_2$	× × ×	To be discussed
$E_7(0,1,1)$	$-\Delta C_x$	$\Delta C_z - A_2 - P_2 - L\omega_2$	$A_2 + \Delta C_y - R - L\omega_2$	- - ×	To be discussed
$E_8(1,1,1)$	ΔC_x	$\Delta C_z - A_2 - P_2 - L\omega_1$	$A_2 + \Delta C_y - P_1 - L\omega_1$	+ × ×	Unstable point

Case I: When $R + L\omega_2 > \Delta C_y + A_2$, $E_7(0,1,1)$ is the stable strategy point of the system.

Case I shows that when the rent-seeking cost is high, the expected accident-related loss is large, the general contractor invests more in safety, the reward amount of the labor subcontractor is relatively low, and the evolution of the strategy combination is stable (Ineffective Supervision, proactive management, active safety investment). This strategy combination is generally conducive to the safe production of construction projects, but it can easily cause problems, such as a waste of resources and a lack of supervision. At this time, the government and the construction employer shall promote the supervision company to organize the staff of each department, send the corresponding functional departments to conduct the supervision work of the construction site according to the actual situation of the project, establish and improve the safety performance assessment system of the supervision company, and encourage the general contractors and the labor subcontractors to report the illegal behavior of supervision companies.

Case II: When $\Delta C_x < L\omega_2$, $\Delta C_z > A_2 + P_2 + L\omega_1$, $E_5(1,1,0)$ is the stable strategy point of the system.

Case II shows that when the opportunity cost of ineffective supervision of the supervision company is relatively high, and the reduced cost of the Passive Safety Investment of the labor subcontractor is higher than the sum of the amount of rewards and punishments. Effective supervision, proactive management, and Passive Safety Investment become the stable strategy combination of the system. Labor subcontractors often lack adequate investment in safety measures, making it challenging to enforce proper qualification checks, safety training, and hazard investigations. As a result, they are unable to deliver high-quality labor dispatch and management services. This not only complicates the oversight responsibilities for supervisory companies and general contractors, but also tends to negatively affect the overall safety performance of the construction project. By enhancing the professional development of construction workers and increasing the subsidies for safety education and training, we can alleviate the economic burden on labor subcontractors. Additionally, by refining the safety performance evaluation criteria for subcontractors and implementing a comprehensive reward-and-penalty system throughout the construction process, we can raise the likelihood of subcontractors proactively investing in safety measures.

Case III: If $\Delta C_z < L\omega_2 P_1 + L\omega_1 < \Delta C_y + A_2$ and $\Delta C_x + R < L\omega_2 + A_1$ both hold true simultaneously, then $E_6(1,0,1)$ is the stable strategy point of the system.

Case III shows that under the condition of a large reward amount, a large expected loss due to accidents caused by two participants, and the low safety investment made by the general contractor, effective supervision, Passive Management, and active safety investment have become the evolution and stability strategy of the system. As the primary entity responsible for safety at the construction site, when the general contractor adopts a passive management approach, the quality of tasks, such as subcontractor qualification review, the formulation of safety construction plans, safety training for workers, and on-site safety supervision, is difficult to ensure. This is not conducive to the safe completion of the construction project. At this time, the probability of active management of the general contractor can be improved by increasing the amount of compensation for a breach of contract and ensuring punishment for safety accidents and increasing the reward for the strict supervision of the supervision company.

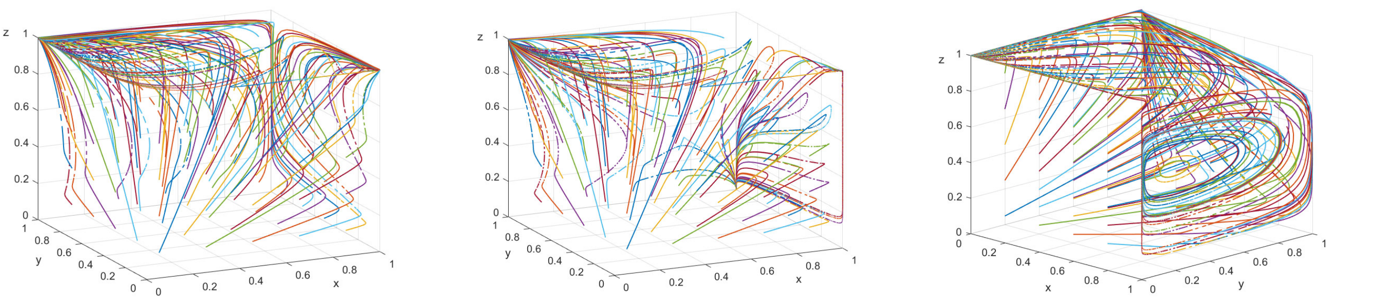
Case IV: When $R + L\omega_2 < \Delta C_y + A_2$, $\Delta C_x + R > L\omega_2 + A_1$, $E_4(0,0,1)$ is the stable strategy point of the system.

Case IV shows that when a supervision company's invalid supervision income is higher, the losses due to the general contractor's passive management are lower, and the best strategy combination to achieve stability is Ineffective Supervision, Passive Management, and active safety investment. At this time, both the supervision company and the general contractor show a negative response to safety management work. In order to mitigate the risk of accidents and avoid substantial losses, labor subcontractors tend to opt for proactive safety investments. Due to the complexity of construction conditions and the construction environment, it is difficult to achieve the goal of safe production only through the management of labor subcontractors. Such evolutionary results should be avoided by building an interested community and increasing the rewards and punishments.

4. Results and Discussion

4.1. Model Valuation and Validity Verification

In order to analyze the influence of the change in each factor on the evolution of the strategy and verify the effectiveness of the model, it is necessary to assign values to the variables. To ensure that the variable values are realistic and that the errors remain within a range that does not affect the outcomes, we consulted the frontline employees of the companies. Based on this, we obtained Array 1, $\Delta C_x = 2.90$, $\Delta C_y = 5.80$, $\Delta C_z = 3.27$, $A_1 = 1.00$, $P_1 = 3.48$, $A_2 = 0.50$, $P_2 = 1.96$, $R = 2.42$, $L = 145$, $\omega_1 = 0.01$, $\omega_2 = 0.03$, $\omega_3 = 0.80$, satisfying cases I and III. To further verify the validity of stability analysis, we took array 2, $\Delta C_x = 2.90$, $\Delta C_y = 5.80$, $\Delta C_z = 4.60$, $A_1 = 1.00$, $P_1 = 3.48$, $A_2 = 0.50$, $P_2 = 1.96$, $R = 2.42$, $L = 145$, $\omega_1 = 0.01$, $\omega_2 = 0.03$, $\omega_3 = 0.80$, satisfying cases I and II. We also took array 3, $\Delta C_x = 3.90$, $\Delta C_y = 5.80$, $\Delta C_z = 3.27$, $A_1 = 1.00$, $P_1 = 3.48$, $A_2 = 0.80$, $P_2 = 1.96$, $R = 0.90$, $L = 105$, $\omega_1 = 0.01$, $\omega_2 = 0.03$, $\omega_3 = 0.80$, satisfying case IV. Using MATLAB 2016b for three sets of values, numerical simulations were performed. According to the simulation results of Figure 1, the evolutionary stability points of Array 1 are $(1,0,1)$ and $(0,1,1)$, and those of Array 2 are $(0,1,1)$ and $(1,1,0)$, and those of Array 3 are $(0,0,1)$, which are consistent with the results of the stability analysis of the equilibrium points given above.



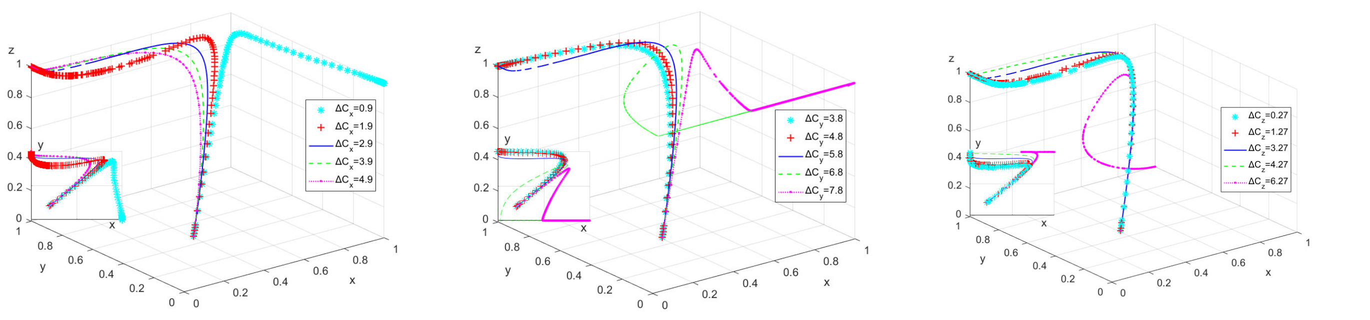
(**a**) Array 1 evolves 50 times. (**b**) Array 2 evolves 50 times. (**c**) Array 3 evolves 50 times.

Figure 1. The evolution path simulation.

4.2. Univariate Sensitivity Analysis

4.2.1. Impacts of Safety Investment on System Evolution

Firstly, to analyze the impact of changes in safety investment on the evolutionary game process and outcomes, ΔC_x is assigned the values $\Delta C_x = 0.9, 1.9, 2.9, 3.9, 4.9$, respectively; ΔC_y is assigned the values $\Delta C_y = 3.80, 4.80, 5.80, 6.80, 7.80$, respectively; and ΔC_z is assigned the values $\Delta C_z = 0.27,\ 1.27,\ 3.27,\ 4.27,\ 6.27$, respectively. The simulation results are shown in Figure 2.



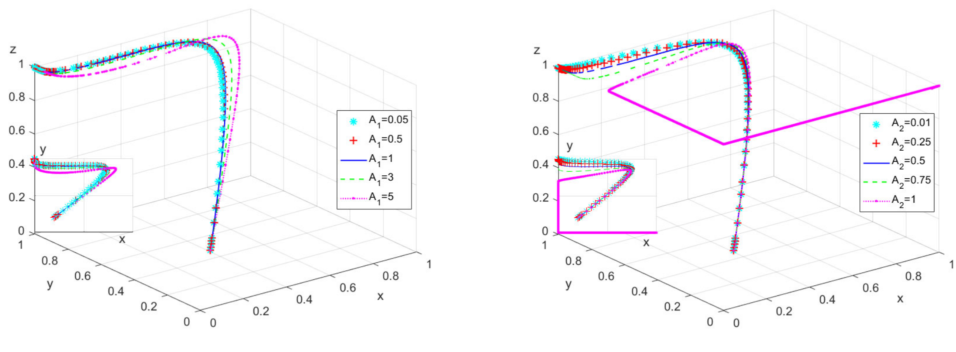
(**a**) (**b**) (**c**)

Figure 2. Impacts of safety investment on system evolution. (**a**) Impacts of ΔC_x on system evolution. (**b**) Impacts of ΔC_y on system evolution. (**c**) Impacts of ΔC_z on system evolution.

Figure 2a indicates that the probability of proactive management by the general contractor decreases as ΔC_x decreases. At this point, the quality of the general contractor's safety construction technical plans and safety education and training may be affected. Appropriately increasing the intensity of the rewards and punishments for the general contractor is beneficial for improving the efficiency of the evolution. As shown in Figure 2b, an increase in ΔC_y is conducive to the improvement of the probability of effective supervision by the supervision company. However, when ΔC_y is large, the evolutionary process is slow, and there is a tendency for a lack of supervision by both the supervision company and the general contractor. In such cases, the measures outlined in case IV should be taken to increase the rate of evolution; Figure 2c indicates that an increase in the labor subcontractor's safety investment tends to lead to a decrease in the probability of effective supervision by the supervision company. Moreover, during the evolutionary process, as the labor subcontractor's safety investment increases, the probability of proactive management by the general contractor also decreases. Therefore, while measures are taken to enhance the supervision company's initiative, it is also necessary to prevent the issue of management laxity by some general contractors during the evolution process.

4.2.2. Impacts of Reward Amounts on System Evolution

Next, to analyze the impact of changes in the reward amount on the evolutionary game process and outcomes, A_1 is assigned the values $A_1 = 0.05, 0.50, 1.00, 3.00, 5.00$, respectively; and A_2 is assigned the values $A_2 = 0.01, 0.25, 0.50, 0.75, 1.00$, respectively. The simulation results are shown in Figure 3. Figure 3a indicates that an increase in the rewards given by the construction employer to the supervision company slows down the evolutionary process. As the reward amount increases, there is a slight decrease in the probability of proactive management by the general contractor during evolution. Therefore, it is necessary to prevent periodic passive management by some general contractors. Figure 3b shows that when the general contractor's reward amount to the labor subcontractor is low, $(0, 1, 1)$ is the system's stable strategy point. As the reward amount increases, the probability of proactive management by the general contractor significantly decreases, the supervision company gradually tends to choose effective supervision, and the rate of evolution noticeably slows down. When the reward amount is substantial, there is a tendency for the simultaneous absence of management by both the supervision company and the general contractor during the evolutionary process. Therefore, changes in A_2 can have a more complex impact on the strategic choices of the supervision company and the general contractor. It is necessary to consider measures from cases I, III, and IV comprehensively to motivate the supervision company and the general contractor to actively participate in safety management and to accelerate the system's evolution.

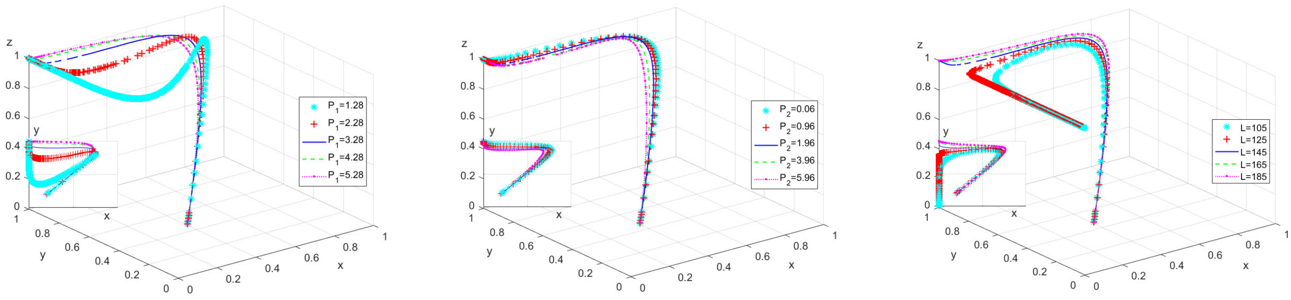


(**a**) (**b**)

Figure 3. Impacts of reward amounts on system evolution. (**a**) Impacts of A_1 on system evolution. (**b**) Impacts of A_2 on system evolution.

4.2.3. Impacts of Breach Compensation Amounts and Accident-Related Losses on System Evolution

To analyze the impact of breach compensation amounts and accident-related losses on the evolutionary game process and outcomes, P_1 is assigned the values $P_1 = 1.28, 2.28$, 3.28,4.28,5.28, respectively; P_2 is assigned the values $P_2 = 0.06, 0.96, 1.96, 3.96, 5.96$, respectively; and L is assigned the values $L = 105, 125, 145, 165, 185$, respectively. The simulation results are shown in Figure 4.



(**a**) (**b**) (**c**)

Figure 4. Impacts of breaching compensation amounts and accident-related losses on system evolution. (**a**) Impacts of P_1 on system evolution. (**b**) Impacts of P_2 on system evolution. (**c**) Impacts of L on system evolution.

Figure 4a indicates that the breach compensation amount of the general contractor does not affect the evolutionary trend, but it has a significant impact on the speed of evolution and the strategic choices made during the evolutionary process. When the compensation amount is low, the system's evolutionary rate is slow, and the probability of proactive management by the general contractor during evolution is relatively low. Therefore, appropriately increasing the breach compensation amount for the general contractor is beneficial for constraining the behavior of the general contractor and accelerating the system's evolution; Figure 4b shows that an increase in the breach compensation amount for the labor subcontractor is conducive to enhancing the evolutionary speed, leading the labor subcontractor to choose an active safety investment strategy sooner. Figure 4c indicates that as the loss from accidents increases, the probability of proactive management by the general contractor significantly improves, and it is beneficial to increase the probability of effective supervision by the supervision company during the evolutionary process. Therefore, increasing the penalties for the parties responsible for accidents and limiting their bidding activities is essential to incentivize all the parties to invest in safety management.

4.2.4. The Impact of Rent-Seeking Amounts on System Evolution

Finally, to analyze the impact of rent-seeking amounts on the evolutionary game process and outcomes, R is assigned the values $R = 0.42, 1.42, 2.42, 3.42, 4.42$, respectively. The simulation results are shown in Figure 5. This indicates that a reduction in the rent-seeking costs can slow down the rate of evolution. As the rent-seeking costs decrease, the probability of effective supervision by the supervision company significantly increases, while the probability of proactive management by the general contractor significantly decreases. There is an issue of the supervision company's management being absent during the evolutionary process, which improves as the rent-seeking amounts are further reduced. Therefore, while combating rent-seeking behavior, attention should also be paid to the issue of passive management by some general contractors and periodic, ineffective supervision by some supervision companies.

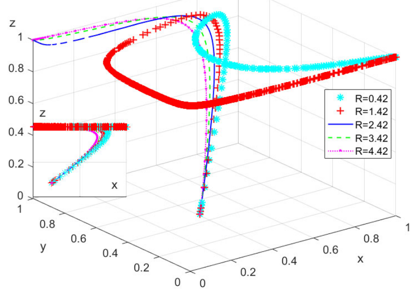


Figure 5. The impact of rent-seeking amounts.

5. Conclusions and Implications

5.1. Conclusions

Differing from the existing literature, which primarily focuses on workers' behavior and governmental regulatory oversights, this paper investigates the interactive dynamics of interested relevant enterprises, while fully considering strategic evolution under labor subcontracting. By constructing a tripartite evolutionary game model between the supervision companies, the general contractors, and the labor subcontractors, this study explores the methods to encourage enterprises to fulfill their safety responsibilities. This research represents an extension of a study on the safety management game theory, offering both theoretical contributions and practical significance. The main findings of this paper are as follows:

(1) Through the analysis of stable strategies, it was found that the contradiction between safety investment and accident-related losses is the core contradiction among the three parties. All the three participants minimize safety investment under the premise of small expected losses, so the strategy combination of effective supervision, proactive management, and active safety investment cannot be realized. Strictly cracking down on negative management and Passive Safety Investment, reasonably controlling the amount of the reward, and increasing the punishment intensity of safety accidents are conducive to enhancing the initiative of general contractors and labor subcontractors in safety management.

(2) Under the premise of a perfect reward-and-punishment system, active safety investment is the evolution and stability strategy of the labor subcontractor. The amount of reward and punishment, accident-related losses, and safety input are the most important factors to determine the evolution and stability strategy of the labor subcontractor. Under the condition of the strict implementation of legal provisions and a clear reward-and-punishment system, the probability of a labor subcontractor choosing active safety investment gradually increases with time.

(3) According to the simulation results, it is challenging to achieve simultaneous diligence on the part of both the supervision companies and the general contractors. Reducing the safety investment of general contracting and labor subcontractors, increasing the rewards for labor subcontractors, and combating rent-seeking behaviors between the supervision companies and the general contractors can encourage supervision companies to opt for effective supervision. Reducing the safety investment by supervision companies, decreasing the amount of rewards for labor subcontractors, increasing the penalties for safety incidents, and enhancing the costs associated with rent-seeking activities are conducive to general contractors choosing proactive management.

(4) The safety input of the general contractor, the amount of rent-seeking, the amount of a reward given to the labor subcontractor, and the accident-related losses have a great impact on the evolution direction of the system. Strictly supervising the safety input status of the general contractors, increasing the compensation for the breach of contract of the general contractors and increasing the punishment for safety accidents are conducive to improving the evolution speed, and thus saving social resources.

It can be observed that given the clarity of rewards and punishments, labor subcontractors are more likely to opt for an active safety investment strategy. However, due to the lack of alignment in interests between the supervision company and the general contractor regarding safety investments, the amount of rewards for labor subcontractors, and the amount of rent-seeking, it is difficult to achieve joint diligence. Therefore, while ensuring the proactive safety investments of labor subcontractors, it is necessary to explore the methods that promote the establishment of concurrent diligence between the supervision companies and the general contractors during the construction process:

(1) It is essential to strengthen the management of construction labor subcontracting contracts by incorporating the safety supervision reward and the penalty mechanisms into the labor subcontracting bidding contracts and by reasonably controlling the

amount of rewards. The stringent oversight of the contract performance during the construction process is necessary; if frequent safety hazards occur at the construction site, the general contractor will be held accountable.

(2) It is imperative to enhance surveillance throughout the construction process, particularly to rigorously combat the rent-seeking behaviors between the supervision units and the general contractor.

(3) It is crucial to reinforce the division of labor and coordination among the organizations at the construction site, clearly defining their respective responsibilities, penalizing "free-riding" behaviors, and fostering a positive safety culture of mutual cooperation.

5.2. Limitations and Future Work

Although this study has made certain contributions to revealing the fundamental issues in construction safety management and redefining stakeholders, there are still some limitations. Firstly, to facilitate the readers' understanding of the calculation process, this study has reasonably simplified the factors with a minor impact on the variable values, without affecting the system's evolutionary outcomes. However, in actual construction projects, there is a possibility of being influenced by unforeseen factors, which may introduce some degree of deviation. Additionally, this study primarily focuses on the implementation of construction safety responsibilities in general building projects in China. As for whether the research findings are applicable to all types of construction projects, we maintain a modest and cautious attitude. Building on this, our research team's future plans are as follows: (1) to continue exploring the evolution of regulatory behaviors among participating entities in different types of construction project, and (2) to consider more complex factors when setting the variables, attempting to present them in the form of functions where possible.

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