ISSN 1392-3730/eISSN 1822-3605

JOURNAL of CIVIL ENGINEERING and MANAGEMENT

2024
Volume 30
Issue 4
Pages 307–325
https://doi.org/10.3846/jcem.2024.21175

INTEGRATING EVOLUTIONARY GAME AND SYSTEM DYNAMICS FOR MULTI-PLAYER SAFETY REGULATION OF MAJOR INFRASTRUCTURE PROJECTS IN CHINA

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Article History:
- received 20 September 2022
- accepted 10 March 2024

Abstract. Aiming at safety regulation in the operation of major infrastructure projects (MIPs) to prevent potential risk loss and adverse social impacts, this research presents a novel model integrating evolutionary game and system dynamics (SD) for optimizing safety regulation strategies with different stakeholders involving the operating company (OC), government section (GS), and public under the bounded rationality, where the evolutionary game theory is applied to describe the interactions among stakeholders in the safety regulation of MIPs followed by simulating through adopting the SD to analyze the effects of different strategies on equilibrium solutions and the stability of game equilibrium. In view of the simulation results based on five scenarios, the dynamic penalty-incentive scenario not only effectively restrains the fluctuations of the strategy selection, but also provides an ideal evolutionary stable strategy, in which the OC could nearly choose to comply with the regulations, while the public could nearly choose to supervise the OC as their optimal strategy to prevent risks. All results indicate that the application of the evolutionary game with the SD model is an effective way to analyze the effects of different strategies and provide effective solutions to study complex multi-player game problems. Overall, this research contributes to developing an evolutionary game with the SD model for the safety regulation of MIPs, which can serve as a platform to identify reasonable regulatory strategies with great practical application.

Keywords: major infrastructure projects, safety regulation, evolutionary game analysis, system dynamics, multi-player game.

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1. Introduction

Major infrastructure projects (MIPs) refer to large-scale, complex, and critical public infrastructure projects that significantly impact the economy, society, environment, politics, security, and safety of wide regions or even the whole country (Chen et al., 2022; Lv et al., 2022; Zeng et al., 2015). Their powerful functions make them gain widespread attention and application. Over the world, many MIPs have been built and operated to play their roles and impacts on the economy and society, such as the Bundesautobahn (BAB) 20 Motorway in Germany, the WATERgraafsmeer (WGM) Program in the Netherlands, the High Speed Two in the UK, the Akshardham Temple Complex in India, the Belo Monte Dam in Brazil, and the Miryang Transmission Tower in Korea (Wang et al., 2020). Especially in China, the construction and operation of a series of MIPs have received great attention, such as the Three Gorges Dam, West-East National Gas Transmission Projects, and the Hong Kong-Zhuhai-Macao Bridge (Luo et al., 2024; Sheng, 2018; Xue et al., 2020). Complexity and uncertainty are endemic in MIPs, coupled with less prior experience and varieties of stakeholders, which adds great difficulty to the safe operation of MIPs and puts quite pressure on their safety regulation (Guo et al., 2014; Li et al., 2016; Shi et al., 2020; Xue et al., 2020). Therefore, more consideration has become given to safety regulation instead of the previous focus on economic benefits to the Gross Domestic Product (GDP) in view of the broad social impacts and substantial potential risks of MIPs (Wang et al., 2016).

The safety regulation of MIPs includes many stakeholders, such as the operating company (OC), government

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section (GS), and the public, where the OC is responsible for the day-to-day operation of the MIP and ensuring its operational safety; the GS's role is to uphold social stability and enhance the well-being of the public, with oversight over the OC and responsibility for ensuring the operational safety of MIPs falls within its jurisdiction; and as for the public, they are the cornerstone of society, as well as the beneficiaries and taxpayers, and have the right to report and supervise any unsafe occurrences in society, including the operational safety of MIPs, additionally, the government actively encourages public participation in safety regulations (Chinese People's Congress, 2021). These factors collectively make them all crucial stakeholders in the safety regulation of MIPs. In the face of the complex and uncertain environment inside and outside MIPs, those stakeholders may develop varying perceptions of risk, even when confronted with the same risks. These differences in risk perception can arise from variations in roles, understanding, interests, and access to complete information, among other factors. This divergence in risk perception can subsequently impact their decision-making regarding safety management, consequently influencing the overall safety operations of MIPs (Boateng et al., 2015). Furthermore, the multitude of diverse and conflicting interests among stakeholders can lead to conflicts that have negative implications for the functioning of MIPs. Failure to address and meet the concerns and expectations of these stakeholders can result in project failure or significant setbacks. Additionally, the complexity of interaction interfaces, coupling of uniqueness and individuality, less prior experience, along with the diversity of stakeholders can further complicate the safety management of MIPs (Guo et al., 2014). Moreover, the ever-growing number of safety rules and regulations in the industry may be perceived as burdensome by organizations, potentially hindering productivity instead of being viewed as effective tools to enhance safety (Jia et al., 2019). Therefore, skillfully managing stakeholders and making appropriate decision-making are essential in effectively coordinating the relationships with various stakeholders for safety regulation in the operation of MIPs.

Up to the present, numerous scholars have made unremitting efforts to study the safety regulation for decision-making from different perspectives with the promising foundation to explore the safety performance of MIPs, and their proposed methods can be divided into qualitative- and quantitative-based methods, where qualitative-based methods are commonly employed in studying government safety regulation issues. For example, Guo et al. (2014) conducted a study on various MIPs to investigate project governance structures using desktop reviews and interview methods. The aim was to understand how governance arrangements could potentially influence project management while proposing a structured mechanism to identify and manage risks for enhancing projects' operational safety. However, this study may not reveal hidden factors, and its reliability may be challenging to assess. While quantitative-based methods are generally applied for safety regulations because they are objective and reliable. Since safety regulation involves decision-making, integrating decision-making theory with risk analysis can provide reference information for safety management in MIPs. For instance, Kardes et al. (2013) and Wang et al. (2016) analyzed the risk factors of MIPs and presented a framework as a decision tool to assess the risk based on prospect theory, self-justification theory, sunk cost effect, and an adapted Analytic Hierarchy Process (AHP) methods, respectively, to determine the safety status of MIPs. While these methods primarily identify risk factors, the uncertainty and complexity of MIPs and inevitable subjectivity in risk analysis limit the widespread application of these methods. In practice, the risk analysis is usually conducted by the regulated OC, whose intentions for pursuing self-interests make them tend to provide inaccurate information to the GS. As a result, the GS has reasonable doubt about the accuracy of the information and obtains reliable information through regulation and public disclosure (Xue et al., 2021). This leads to strategic interactions among the GS, OC, and public. However, the risk analysis by integrating decision theory is oriented to the decision-making of a single decision-maker and may not be suitable for the decision-making involved in the strategic interactions of three players.

Game theory allows studying interactions among multiple decision-makers to determine optimal strategies considering the involved process and constraints (Ji et al., 2021; Nana et al., 2022; Zhu et al., 2022b). For example, Assaad et al. (2021) proposed an algorithmic game theory based approach to determine the bidding decision with the optimal outcome in the long run, and the results showed that it can provide positive outcomes to help owners in bidding. Similarly, Sun et al. (2023) constructed a stakeholder interaction model based on an evolutionary game to study the strategies of three stakeholders in applying Building Information Modeling (BIM) for Engineering Procurement-Construction (EPC) projects, which analyzes the interactive behaviors of the government, the owner, and the general contractor based on the assumption of bounded rationality, and finally obtained good results. Dou et al. (2023) proposed a tripartite evolutionary game model of government, developers, and contractors based on prospect theory, which can be applied to prefabricated construction to analyze the development of this field, and the results indicated that the method can yield effective outcomes. These studies have been applied in the field of engineering and construction based on game theory with promising results, but rarely on the safety regulation of MIPs even if MIPs have great impacts on the economy and society. In addition, players have generally bounded rationality in operation, and they can dynamically adjust their strategies by observing and comparing profits with others. In light of that, the evolutionary game theory is suitable for describing the long-term dynamic process of multi-player gameplay in the safety regulation of MIPs under bounded rationality. Similar to biological evolution

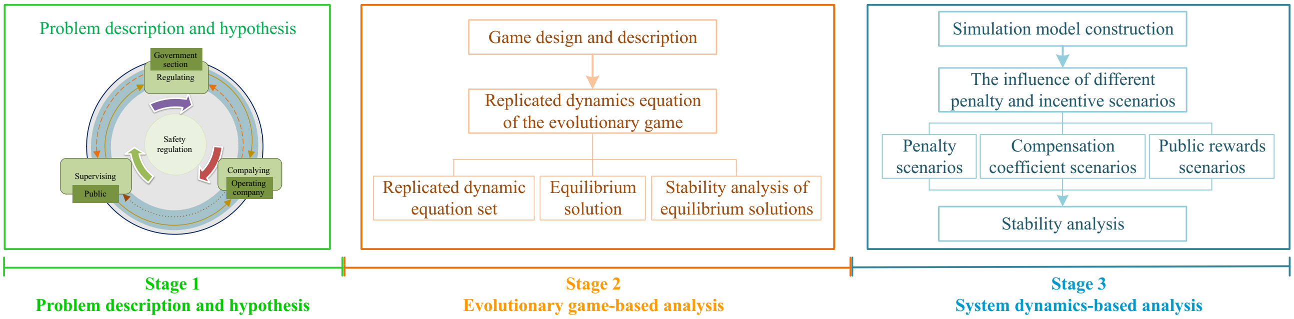


Figure 1. Framework of the proposed model

theory, the evolutionary game theory suggests that individuals are capable of achieving the optimal result, namely game equilibrium, through trial and error or constant selection to adjust strategies by learning from observation, which is consistent with reality (Friedman, 1991). Additionally, to further explore the influence of different factors on the game process and results, the system dynamics (SD) is adopted to analyze interactions among stakeholders for capturing the dynamic behaviors of overall modeling and simulation on the game process and the game equilibrium in various scenarios, which contributes to effectively develop and implement regulatory strategies for GS. A framework of the proposed model is presented in Figure 1, in which the problem description and hypothesis of MIPs are introduced to put out the issues exited in the operation of MIPs, upon that the evolutionary game is applied to analyze the interactions among various stakeholders, and then the SD is employed to simulate different scenarios for optimal the management strategy.

The remainder of this research is organized as follows. First, the related works on the safety of MIPs and the integration of evolutionary game and system dynamics are discussed to analyze the current research gap. Next, the multi-player evolutionary game analysis of MIPs on safety regulation is introduced. Afterward, the multi-player evolutionary game simulation based on SD is provided, including simulation model construction and strategy simulation results. Subsequently, the discussions are presented. Lastly, presenting the conclusions and future works.

2. Related studies

MIPs play pivotal roles in promoting economic development and supporting social prosperity and stability (Bovensiepen & Meitzner Yoder, 2018; Lin et al., 2017; Zeng et al., 2015), and their safe operation thus has attracted attention from various parties, ranging from government leaders down to the general public, but still presents many challenges. In this section, the primary focus is the works on MIPs with different methods related to managing the safety of MIPs. In addition, applications from the relevant literature on the integration of the evolutionary game and SD in various fields are presented. In light of that, those existing studies will be analyzed and then the research gaps will be summarized as significant information to carve out targeted problem statements that will subsequently be addressed in this research with the developed method.

Thanks to the unremitting endeavors of numerous scholars, fruitful works have been carried out to study risks for ensuring the safety of MIPs. For example, Erol et al. (2020, 2022) explored in detail the relationship between complexity and risk and proposed integrated risk assessment approaches based on both quantitative and qualitative methods, including an interview procedure, and an Analytic Network Process (ANP) model, respectively, to risk analysis for megaconstruction projects. These methods were applied to 11 megaconstruction projects for risk assessment and the results showed that it can assist practitioners to develop better risk management plans. Likewise, Coskun et al. (2023) developed a risk assessment method, namely Risk Assessment Method for Sustainable Construction Objectives in Megaprojects (RAMSCOM), for sustainable risk assessment of mega construction projects. This method utilizes the hierarchical analysis method (AHP) and cross impact analysis (CIA) to identify and quantify threats related to the importance of the sustainability objectives, and its effectiveness was validated on a major project. Accordingly, Castelblanco et al. (2024) presented a multilayer network analysis method to quantitatively assess risk propagation and its impact on project outcomes. This method combines economic transactions between stakeholders with risk to to gain a comprehensive understanding of the whole system and was validated in a real magaproject to demonstrate the performance of the method. While those methods, which consider internal or external factors of the project to ensure the safety of major projects, have achieved good results in specific scenarios and contributed to the advancement of the research field and the enrichment of the knowledge pool, most of them are not suitable for multiple stakeholders with effective strategies to handle dynamic interactions in guiding the management of MIPs within the complex and uncertain environments.

Recently, the integration of the evolutionary game and SD with their superior performance has been applied to several fields to study multi-parter long-time dynamic interactions. providing effective results with wide promise, where the evolutionary game is able to analyze the game-playing process within the bounded rationality of players to determine strategies depending on their own goals (Eid et al., 2015; Lv et al., 2021), while the SD is an effective computer-based simulation method primarily used for understanding and representing complex systems and analyzing their dynamic behaviors through the feedback system based on its foundation of systems thinking with incomplete information (Aladağ & Işik, 2020; Ansari, 2019), which is suitable for complex decision problems and flexible model structures to capture the relations among diverse variables through qualitative and quantitative simulations (Ecem Yildiz et al., 2020). Those applied fields include but are not limited to green supply chain management in manufacturing (Tian et al., 2014), coal mine safety inspection (Liu et al., 2015, 2019; You et al., 2020), construction projects (Guo et al., 2018; Zuo et al., 2022), policy effects (Zhou et al., 2019; Zhu et al., 2020a, 2022a), manufacturer's emissions abatement behavior (Zhang et al., 2019), transboundary water sharing problem (Yuan et al., 2020), rail transportation safety regulation (Feng et al., 2020), and predictive maintenance technologies (Meng et al., 2022). For example, Liu et al. (2019) integrated the evolutionary game and SD applied to the coal mine industry for safety regulation by considering coal mine regulators and coal mine enterprises, where the evolutionary game is employed to describe the long-term dynamic process of a multiplayer game in coal mine safety regulation under bounded rationality, while the SD simulates the process of a multiplayer evolutionary game to analyze the effects of different punishment strategies on the game process and the game equilibrium. Likewise, Feng et al. (2020) proposed a method to regulate railway transportation safety based on the evolutionary game and SD, which introduced the public supervision mechanism to form a tripartite regulatory system, including the State Railway Administration, China Railway Corporation, and the public. The method provides several beneficial findings by simulating the decision-making process, which facilitates the construction of a more reasonable regulatory mechanism. Accordingly, Zuo et al. (2022) applied an evolutionary game with the SD to a construction project to model the rent-seeking problem of participants in order to prevent performance damage, this method analyzed the behavioral characteristics and interactions of owners, supervisors, and contractors, to explore the impact of multiple factor changes on participants' rent seeking decisions to assist project owners in taking appropriate measures. The integration of evolutionary games and SD allows to analyze the behaviors and interactions of multiple stakeholders and to simulate the impacts of different factors on the outcome for exploring future developments. Those successful applications motivate the authors to explore its performance in MIPs to ensure safe operations.

In summary, most of the studies have attained favorable results, both in terms of different methods applied to MIPs and the integration of the evolutionary game with SD used in other fields. However, most of the existing studies lack the analysis of dynamic long-term interactions of multiple stakeholders with integrating the evolutionary game and SD on MIPs, which has the potential for further exploration. In view of those and motivated by the successful applications of integrating evolutionary game and SD, this research endeavors to develop an evolutionary game with the SD model on MIPs, aiming to analyze the interactions of different stakeholders on MIPs, simulate the effects of different strategies changes on the equilibrium solutions, and assess the stability of game equilibrium. The novelty of this research lies in constructing a game analysis model based on a comprehensive consideration of the influence factors of different stakeholders, such as GS, OC, and the public, and describing the interactions among these stakeholders through an evolutionary game, upon which, the SD is used to simulate their interactions to analyze the effects of different strategy changes on the game process in different scenarios, which can reveal the behavioral and interaction changes in the coming time period, and then exploring the stable state and equilibrium values for the safety regulation of MIPs to guide managers to take appropriate measures. This model can serve as a platform to identify reasonable regulation strategies to facilitate the safe operation of MIPs.

Abbreviations

MIPs	Major infrastructure projects
OC	Operating company
GS	Government section
SD	System dynamics
ES	Equilibrium solution

Symbols in the multi-player game

Symbols	Meaning	Note
x	Probability of complying with the regulations	$0 \le x \le 1$
y	Probability of regulating	$0 \le y \le 1$
z	Probability of supervising	$0 \le z \le 1$
B_e	Profit of the OC	$B_e > 0$
c_a	Cost of the OC caused by compliance with the regulations	$c_a > 0$
c_p	Cost of the public for choosing to supervise the OC	$c_p > 0$
P	Penalties of the OC not complying with the safety regulations	$P > 0$
P'	The dynamic penalty strategy in the safety regulation of MIPs	$P' > 0$
P''	The dynamic penalty strategy in the optimal dynamic penalty-incentive scenario	$P'' > 0$
θ	Incentive coefficient for the OC	$\theta \ge 0$
μ	Extra loss coefficient of collaboration	$0 \le \mu \le 1$
η	Extra loss coefficient of supervision	$\mu \le \eta \le 1$
λ	Profit tax rate	$0 \le \lambda \le 1$
c_g	Regulation cost of the GS	$c_g \ge 0$
T_g	Social benefits of regulating the OC	$T_g \ge 0$
S_g	Social distrust of not regulating the OC	$S_g \ge 0$
PB	Perceived benefits of the public	$PB \ge 0$

Symbols	Meaning	Note
B_p	Public rewards	$B_p \geq 0$
L	Loss caused by the OC circumventing safety regulations	$L > 0$
ε	The proportion of the GS and the public to share loss L	$0 \leq \varepsilon \leq 1$
k	Discount coefficient of loss with the supervision of both the GS and public	$0 \leq k \leq 1$
m	Discount coefficient of loss with the supervision of the public	$k \leq m \leq 1$
n	Discount coefficient of loss with the regulation of the GS	$m \leq n \leq 1$
C_d'	The dynamic compensation	$(\theta c_a)' \geq 0$
T_g'	The dynamic improvement of public credibility	$T_g' \geq 0$
S_g'	The dynamic loss of public credibility	$S_g' \geq 0$
PB'	The dynamic public's perceived benefits	$PB' \geq 0$
R_1	Execution of regulation duties	/
R_2	Dereliction of regulation duties	/
C_1	Complying with the regulations	/
C_2	Circumventing the regulations	/
P_1	The safety regulation of MIPs with public supervision	/
P_2	The safety regulation of MIPs without public supervision	/
U_{11}	The fitness of complying with the regulations	/
U_{12}	The fitness of circumventing the regulations	/
U_1	The average fitness of the OC	/
U_{21}	The fitness of regulating the OC	/
U_{22}	The fitness of not regulating the OC	/
U_2	The average fitness of the GS	/
U_{31}	The fitness of supervising the OC	/
U_{32}	The fitness of not supervising the OC	/
U_3	The average fitness of the public	/

3. Multi-player evolutionary game analysis of MIPs on safety regulation

The evolutionary game theory has been extensively applied in many fields, including but not limited to bidding (Ho & Hsu, 2014), reconstruction of buildings (Yang et al., 2019), environmental regulation (Sheng et al., 2020), construction waste recycling management (Ma & Zhang, 2020), and supply chain (Zhou et al., 2020). Those fruitful results enrich the knowledge pool and contribute to its continued advancement. However, the evolutionary game theory has been rarely employed in the safety regulation of MIPs, allowing the possibility for further exploration.

3.1. Problem description and hypothesis

In the operations of MIPs, many stakeholders are involved, both as executors and managers, and different stakeholders may fall into disagreement and conflict due to inconsistent pursuit and actions (Aladağ & Işik, 2020; Li et al., 2012, 2013), which increases the difficulty of implementing safety regulations. This research, thus, tries to simplify the problem while ensuring the description of the complex problem in the safety regulation of MIPs. From the perspective of safety regulation and stakeholder responsibility, the GS and OC are included as stakeholders in the problem analysis. In addition, the public is introduced into the safety regulation system because the public, as the beneficiaries and taxpayers of MIPs, has the right and responsibility to supervise the safe operations of MIPs (Jiang et al., 2016; Lee et al., 2017). In light of the roles and functions of different stakeholders, interactions and conflicts are, in fact, inevitable due to differences in the objectives and goals pursued. In addition, given that the OC, GS, and public are generally in unequal positions, the implementation of safety regulations is more a game than a multilateral negotiation.

Bearing the above analysis, the pure strategy faced by the OC, is whether to comply with safety regulations in the operation of MIPs or not, referred to as "complying" and "circumventing" (Wang et al., 2009). The reasons for those strategies to exist are that compliance is able to avoid penalties from GS while circumvention may obtain more benefits with the possibility of being penalized. For the GS, it can choose to regulate the OC for ensuring the safe operation of MIPs. However, the GS needs to deal with numerous miscellaneous matters so as not to guarantee all-weather regulations. As a result, the GS also faces two pure strategies: regulating the OC or not, referred to as "regulating" and "not regulating". If the GS performs regulation, the GS will pay out some regulation costs but gain benefits, such as reduced social risks, social recognition, and tax revenue; while if the GS does not perform regulation, it saves regulation costs but may result in the existence of risks and the loss of social recognition, possibly causing the loss of greater costs. Similarly, the public can choose to supervise the GS and OC or take no action, referred to as "supervising" and "not supervising" (Gao et al., 2022). Here, a logical assumption is that the GS and the public have strong abilities to successfully discover any violation during the inspection.

The relationships among the three stakeholders in the safety regulation of MIPs are shown in Figure 2. In the in-

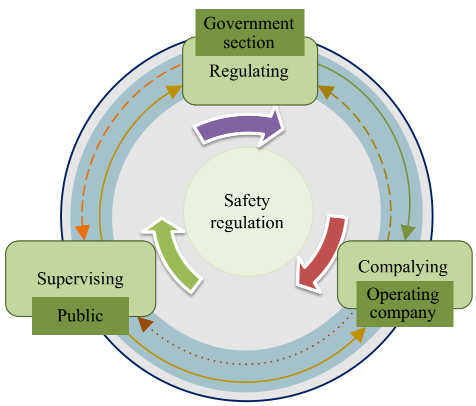


Figure 2. Multi-player game in safety regulation of MIPs

teraction process, the profits of the GS, OC, and the public would depend on each other's strategic choices, but also suffer from the loss risk. As the bounded rational and economic individual, the GS, OC, and public act to maximize their interests, but from the functional perspective of MIPs, need to guarantee the safe operation of MIPs to promote economic development and social prosperity. Thus, the objectives of safety regulation will be met when the outcome of the game is that the safety regulations can be effectively implemented.

3.2. Game design and description

In accordance with the above analysis, in this game, each participant has two alternative strategies to choose from, resulting in eight different strategy combinations. Referring to relevant studies (Gao et al., 2022; Wang et al., 2009), the detailed expressions of the eight different strategy combinations for the three stakeholders are shown in Tables 1 and 2. In line with the fact that each participant is a bounded rational, they continuously adjust their strategies to maximize their own interests. Therefore, the strategy they initially choose does not represent the final outcome of the game. Under different combinations of strategies, each participant will get different returns. The analysis is as follows.

1) When the strategy combination is (R_1, C_1, P_1), the GS needs to pay regulation costs and subsidies and receives benefits, so the payoff is $\lambda B_e - c_g - \theta c_a$. The OC can obtain benefits and government subsidies, but needs to pay taxes and costs, so its payoff is $(1-\lambda)B_e - c_a + \theta c_a$. While the public receives the perceived benefits but needs to pay the cost of supervision, so the payoff is $PB - c_p$.

2) When the strategy combination is (R_2, C_1, P_1), the payoff of the GS is λB_e because the GS only obtains the benefits from the OC with no regulation. Upon this, the OC can not obtain the subsidies from the GS, while the PB has the same payoff as that in (1).

3) When the strategy combination is (R_1, C_2, P_1), the OC is punished by the GS and suffers extra losses including the loss of interests indirectly affected by public supervision due to circumventing the regulations. Since the GS performs well in regulation can gain social recognition in addition to tax and penalty gains, and suffers certain risks caused by OC with circumventing the regulations, its payoff is $\lambda(B_e - \mu B_e) - c_g + \mathrm{P} + T_g - k\varepsilon L$. For public, also suffers the risk of circumventing the regulations caused by OC and pays the costs of supervision.

4) When the strategy combination is (R_2, C_2, P_1), the OC is punished by the GS and suffers another extra loss including the loss of interests indirectly affected by public supervision due to circumventing the regulations. Since GS does not perform regulation, it suffers from social distrust and risks caused by OC, pays public rewards, and obtains benefits from the OC. For public, it also suffers the risk of circumventing the regulations caused by OC and pays the costs

Table 1. Profit matrix in the safety regulation of MIPs with public supervision (*z*)

		GS	
		R_1: Execution of regulation duties (y)	R_2: Dereliction of regulation duties ($1-y$)
OC	C_1: Complying with the regulations (x)	$(1-\lambda)B_e - c_a + \theta c_a$	$(1-\lambda)B_e - c_a$
		$\lambda B_e - c_g - \theta c_a$	λB_e
		$PB - c_p$	$PB - c_p$
	C_2: Circumventing the regulations ($1-x$)	$(1-\lambda)(B_e - \mu B_e) - P$	$(1-\lambda)(B_e - \eta B_e) - P$
		$\lambda(B_e - \mu B_e) - c_g + \mathrm{P} + T_g - k\varepsilon L$	$\lambda(B_e - \eta B_e) + \mathrm{P} - S_g - B_p - m\varepsilon L$
		$-c_p - k(1-\varepsilon)L$	$B_p - c_p - m(1-\varepsilon)L$

Table 2. Profit matrix in the safety regulation of MIPs without public supervision ($1-z$)

		GS	
		R_1: Execution of regulation duties (y)	R_2: Dereliction of regulation duties ($1-y$)
OC	C_1: Complying with the regulations (x)	$(1-\lambda)B_e - c_a + \theta c_a$	$(1-\lambda)B_e - c_a$
		$\lambda B_e - c_g - \theta c_a$	λB_e
		0	0
	C_2: Circumventing the regulations ($1-x$)	$(1-\lambda)B_e - P$	$(1-\lambda)B_e$
		$\lambda B_e + \mathrm{P} - n\varepsilon L$	$\lambda B_e - \varepsilon L$
		$-n(1-\varepsilon)L$	$-(1-\varepsilon)L$

of supervision, and obtains the public rewards, so its payoff is $B_p - c_p - m(1-\varepsilon)L$.

5) When the strategy combination is (R_1, C_1, P_2), GS and OC behave the same as in (1), i.e., obtain the same payoffs as in (1), while the public does not participate, so the payoff is 0.

6) When the strategy combination is (R_2, C_1, P_2), GS and OC behave the same as in (2), i.e., obtain the same payoffs as in (2), while the public does not participate, so the payoff is 0.

7) When the strategy combination is (R_1, C_2, P_2), the OC gets the benefit and pays the tax, and suffers the penalty from GS, resulting in the payoff of $(1-\lambda)B_e - P$. GS receives taxes and penalties, but suffers the risk due to circumventing the regulations by the OC, obtaining the payoff of $\lambda B_e + P - n\varepsilon L$. While the public is also at risk due to the circumventing the regulations by OC, resulting in a payoff of $-n(1-\varepsilon)L$.

8) When the strategy combination is (R_2, C_2, P_2), the OC obtains the benefit and needs to pay the tax, thus its payoff is $(1-\lambda)B_e$. The GS only obtains the taxes but suffers the risk due to circumventing the regulations by the OC, getting the payoff of $\lambda B_e - \varepsilon L$, while the public also suffers the risk resulting in the payoff of $-(1-\varepsilon)L$.

3.3. Replicated dynamics equation of the evolutionary game

In light of the hypothesis and variable analysis, this research established the evolutionary game model to quantitatively analyze the changes to the three stakeholders' strategies for the safety regulation of MIPs. In the evolutionary game theory, the replicator dynamic is used to represent the learning and evolution mechanism of stakeholders (Capraro & Perc, 2021; Xia et al., 2023), which can be well applied to the process of safety regulation of MIPs.

For the OC, the expected profits for choosing to comply with the regulations (U_{11}) and for choosing to circumvent the regulations (U_{12}) can be obtained as follows, respectively:

$$U_{11} = (1-\lambda)B_e - c_a + y\theta c_a; \tag{1}$$

$$U_{12} = (1-\lambda)B_e - zP - zy(1-\lambda)\mu B_e - z(1-y)(1-\lambda)\eta B_e - (1-z)yP, \tag{2}$$

where U_{11} and U_{12} are also called the fitness of complying with the regulations and circumventing the regulations, respectively. Based on this, the expected average profit of the OC U_1, namely, the average fitness of OC, can be expressed as follows:

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

For GS, similarly, the expected profit for choosing the execution of regulation duties (U_{21}) and for choosing dereliction of regulation duties (U_{22}) can be obtained as follows, respectively:

$$U_{21} = \lambda B_e + x\left(-c_g - \theta c_a\right) + (1-x)P + z(1-x)\left(-\lambda\mu B_e - c_g + T_g - k\varepsilon L\right) + (1-x)(1-z)(-n\varepsilon L); \tag{4}$$

$$U_{22} = \lambda B_e + z(1-x)\left(-\lambda\eta B_e + P - S_g - B_p - m\varepsilon L\right) - (1-x)(1-z)\varepsilon L, \tag{5}$$

where U_{21} and U_{22} are also called the fitness of regulating the OC and not regulating the OC, respectively. Based on this, the expected average profit of GS U_2, namely, the average fitness of the GS, can be expressed as follows:

$$U_2 = yU_{21} + (1-y)U_{22}. \tag{6}$$

For the public, the expected profit for choosing to supervise the OC (U_{31}) and for choosing not to supervise the OC (U_{32}) can be obtained as follows, respectively:

$$U_{31} = xPB - c_p + (1-x)(-yk(1-\varepsilon)L + (1-y)(B_p - m(1-\varepsilon)L)); \tag{7}$$

$$U_{32} = -(1-x)(yn(1-\varepsilon)L + (1-y)(1-\varepsilon)L), \tag{8}$$

where U_{31} and U_{32} are also called the fitness of supervising the OC and not supervising the OC, respectively. Based on this, the expected average profit of the public U_3, namely, the average fitness of the public, can be expressed as follows:

$$U_3 = zU_{31} + (1-z)U_{32}. \tag{9}$$

According to the fitness of the three stakeholders, the replicator dynamic equations can be obtained. For the OC, the replicator dynamic equation is obtained based on the Equations (1)–(3), as follows:

$$F(x) = \frac{d_x}{d_t} = x\left(U_{11} - U_1\right) = x(1-x)\begin{pmatrix} -c_a + y\theta c_a + zP + zy(1-\lambda)\mu B_e \\ +z(1-y)(1-\lambda)\eta B_e + (1-z)yP \end{pmatrix}. \tag{10}$$

Similarly, the replicator dynamic equations of GS and public are obtained as follows, respectively:

$$F(y) = \frac{d_y}{d_t} = y\left(U_{21} - U_2\right) = y(1-y)\begin{pmatrix} -x\left(c_g + \theta c_a\right) + (1-x)(P + (1-n)\varepsilon L) + \\ z(1-x)\left(T_g - c_g + (m+n-k-1)\varepsilon L + \right. \\ \left. \lambda B_e(\eta - \mu) + S_g + B_p - P\right) \end{pmatrix}; \tag{11}$$

$$F(z) = \frac{d_z}{d_t} = z(U_{31} - U_3) = z(1-z)(xPB - c_p + (1-x)y(n-k)(1-\varepsilon)L + (1-x)(1-y)(B_p + (1-m)(1-\varepsilon)L)). \tag{12}$$

Therefore, the multi-player evolutionary game in the safety regulation of MIPs can be represented by the following replicator dynamic equation set based on the replicator dynamic equations of the three stakeholders:

$$\begin{cases} F(x)=\dfrac{d_x}{d_t}=x\left(U_{11}-U_1\right)=x(1-x)\begin{pmatrix}-c_a+y\theta c_a+zP+zy\left(1-\lambda\right)\mu B_e+\\ z\left(1-y\right)\left(1-\lambda\right)\eta B_e+\left(1-z\right)yP\end{pmatrix}\\ F(y)=\dfrac{d_y}{d_t}=y\left(U_{21}-U_2\right)=y(1-y)\begin{pmatrix}-x\left(c_g+\theta c_a\right)+(1-x)(P+(1-n)\varepsilon L)+\\ z\left(1-x\right)\left(T_g-c_g+\left(m+n-k-1\right)\varepsilon L+\right.\\ \left.\lambda B_e\left(\eta-\mu\right)+S_g+B_p-P\right)\end{pmatrix}\\ F(z)=\dfrac{d_z}{d_t}=z\left(U_{31}-U_3\right)=z(1-z)(xPB-c_p+\left(1-x\right)y\left(n-k\right)\left(1-\varepsilon\right)L+\\ (1-x)(1-y)(B_p+\left(1-m\right)\left(1-\varepsilon\right)L)). \end{cases} \tag{13}$$

In the game process, those stakeholders are not completely independent, and diverse interactions, various incompatible or opposing interests pursued and different requirements inevitably exist in the safety regulation of MIPs, increasing the complexity with a great number of variables and difficulty to find the equilibrium points under various strategies. Although the Jacobian matrix as the theoretical analysis is proposed to obtain the equilibrium solution (ES) for strategies, it is hard to analyze the Jacobian matrix under the complexity and difficulty. Moreover, it is not conducive to grasping the essence of the problem and analyzing the dynamic evolutionary process and the influence of each factor. Therefore, this research adopts the SD method to simulate the scenarios with different strategies for analyzing the complicated evolutionary game processes among the three stakeholders.

4. Multi-player game simulation based on SD

In the above multi-player game, the stakeholders can constantly imitate and learn from the other stakeholders, and then adjust their strategies by observing and comparing the profits of themselves and others, which constitutes the dynamic feedback behavior in the system. Moreover, the information learned and observed from other stakeholders is incomplete, which is in line with the fact that some variables are hard to quantify accurately. By considering those factors, the SD is suitable for this research to analyze the long-term game relationships and dynamic behaviors among stakeholders and to explore the influence of various factors, thus providing an effective experimental platform for determining reasonable strategies.

4.1. Simulation model construction

In view of the above multi-player game assumptions and analysis, the Vensim® PLE 8.1.2 is applied to draw the system flow diagram to simulate the complex interactions for the safety regulation of MIPs. According to the above game assumptions and analysis, OC, GS, and the public have mutual interaction and influence, upon which an SD model is constructed as shown in Figure 3. In this model, the elemental system of the multiplayer SD model is divided into three subsystems: OC, GS, and public, their rela-

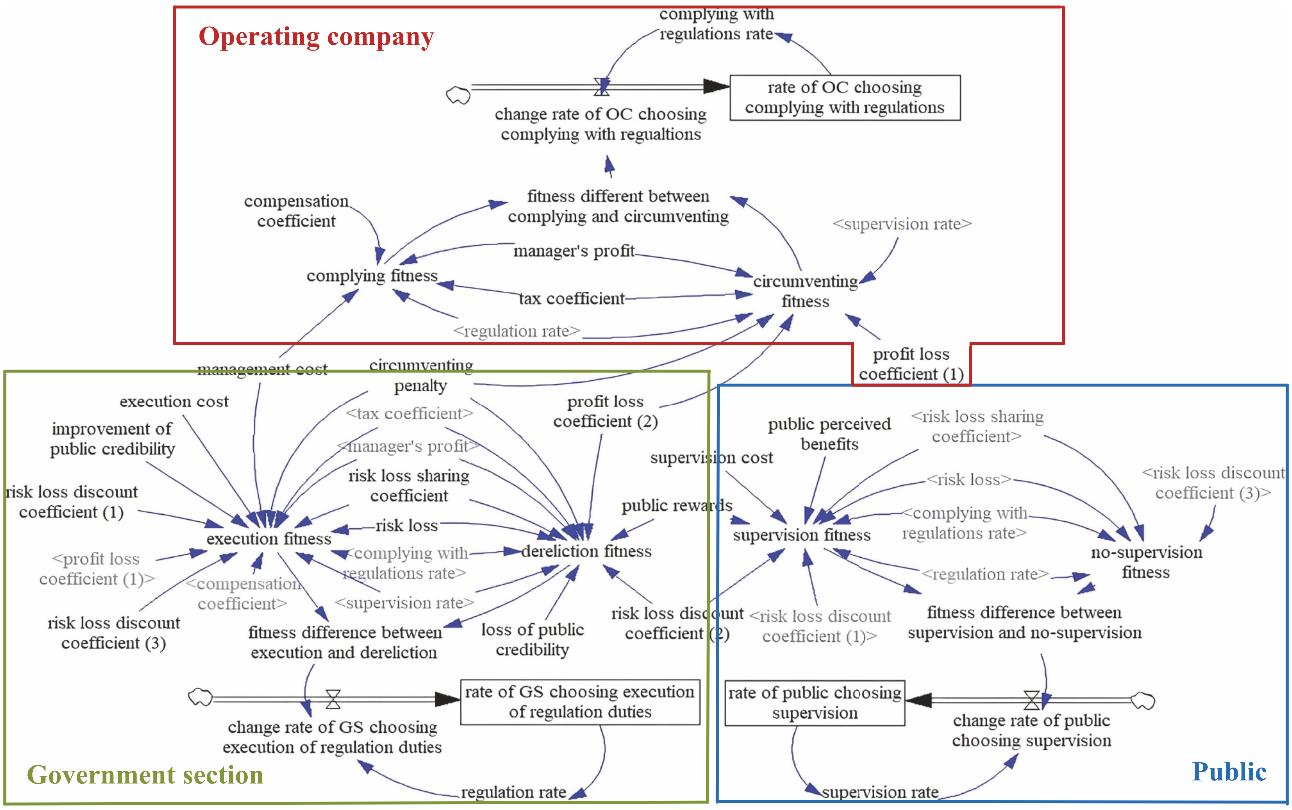


Figure 3. Multi-player evolutionary game with the SD model for safety regulation of MIPs

tionships are established based on Eqn (13). In view of Eqn (13) and Figure 3, it is evident that there are common variables between the three subsystems, meaning that there is a correlation between them, thereby making it possible to analyze their interactions to obtain the ideal evolutionary stable strategy.

According to the operability principle, variables in the multi-player game SD model are divided into four categories: three-level variables, three rate variables, nine auxiliary variables, and eighteen external variables, which can clearly illustrate the system's dynamic behaviors and cumulative effects. Specifically, the three-level variables include the rate of OC complying with regulations, the rate of GS executing the regulations, and the rate of public supervising the OC; the three rate variables consist of the change rate of OC complying with regulations, the change rate of GS executing the regulations, and change rate of public supervising the OC; the nine auxiliary variables are U_{11}, U_{12}, U_1, U_{21}, U_{22}, U_2, U_{31}, U_{32}, and U_3; and the eighteen external variables. The variables and graphical representations in the system flow diagram are shown in Table 3. These level variables are accumulated by rate variables, which are influenced by multiple auxiliary variables and simultaneously affect the overall system state. In this research, the multi-player game SD model aims to effectively explain the complex system problem and find the possible pathways for promoting the sustainable safe operation of MIPs. Additionally, the system flow diagram can simulate a case system of MIPs from an operable, quantitative, and visual perspective.

4.2. Strategy simulation

To conduct the simulation analysis of the evolutionary game with the SD model, this research performs a series of numerical simulations to explain some situations from a scientific perspective. In line with practical projects and relevant studies (He et al., 2020; Li et al., 2018; Tan & Hong, 2021; Yuan & Yang, 2022), and fully considering the complex interactions of MIPs based on the game equation assumption and analysis, the initial values of the B_e and c_a are set at 11.5 and 7, respectively, the λ is 0.15, and the c_g and c_p are set as 1 and 0.5, respectively. Since the occurrence of MIPs risks will bring negative effects to society and the economy, conducting severe punishment is necessary, so the penalty P is initially set as 5, which is slightly greater than the net profit. In addition, the initial values of the other variables are listed in Table 4. To sensitively observe the changes in each player's strategy, the daily changes are simulated in the strategies of the three stakeholders over a 10-year period. The model setting is as follows: INITIAL TIME = 0; FINAL TIME = 3,650; TIME STEP = 1; and Units for Time: Day; Integration Type: Euler.

Therefore, ESs of the replicated dynamic equation set in Eqn (13) are obtained, eight ESs of the pure strategy and two ESs of the mixed strategy are as follows:

$$ES_1=(0,0,0)^T, ES_2=(0,0,1)^T, ES_3=(0,1,0)^T,$$
$$ES_4=(1,0,0)^T, ES_5=(1,0,1)^T, ES_6=(1,1,0)^T,$$
$$ES_7=(0,1,1)^T, ES_8=(1,1,1)^T, ES_9=(34/53, 35/39, 0)^T,$$
$$ES_{10}=(225/1441, 2027/4089, 1)^T.$$

For examining the strategy stability, the ten ESs are input into the SD model for simulation. The simulation results show that the three stakeholders have reached a relatively balanced state, in which no stakeholder actively changes the initial strategy when no one adopts a new strategy. The ES_9, as an example, is shown in Figure 4, whose relatively balanced state occurs in a specific situation, however, it cannot guarantee the long-term stability of the strategy when a stakeholder adjusts its strategy under interference from external factors. For example, if the public slightly mutates their initial strategies from 0 to 0.01, the three stakeholders play a new round of games, and the simulated game results are shown in Figure 5a. As can be seen, the simulation results indicate that the balanced states of ES_9 are unsteady. In other words, once the public slightly changes the initial strategy under interference from external factors, the equilibrium of the game will be broken.

Table 3. Variables of the system flow diagram and graphical representations

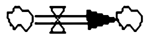
Variable	Meaning of the variable	Icon
Level variable	It is a stock variable that plays a cumulative role and is determined by the input and output flow rate.	Variable name
Rate variable	It is a flow variable, also called the differentiation of stock variable, which depends on the constant and decision variables.	
Auxiliary variable	It is an information variable that describes the process of information transfer between the level variable and the rate variable.	Variable name
Shadow variable	It is a repetitive variable in the system.	<Variable name>
External variable	It is a boundary variable, which determines the system structure and remains unchanged or changes little.	Variable name

Table 4. The variable values

Variable	θ	μ	η	T_g	S_g	PB	B_p	L	ε	k	m	n
Value	0.4	0.05	0.075	0.2	0.4	1	0.7	6	0.6	0.4	0.5	0.5

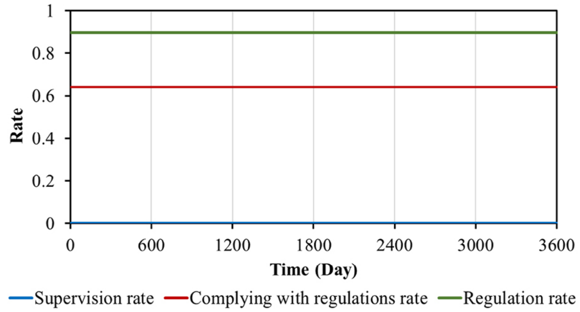


Figure 4. Evolutionary results under the initial strategy ES_9

The resulting scenario is that the strategy selection of the public evolves gradually toward z = 1 while the strategy selection of the OC and GS fluctuates repeatedly. Similarly, the balanced states of ES_1 ~ ES_8 and ES_{10} are all unsteady, two of those simulated game results are shown in Figures 5b and 5c. Those simulation results demonstrate that the evolutionary stability strategy does not exist in multi-player game playing, and those unstable strategies could provide the potential for risk and resource waste.

For further exploring the strategy stability, this research executes more general strategies for simulation. As examples, initial strategies ES_{g1} = $(0.5, 0.5, 0.5)^T$ and ES_{g2} = $(0.6, 0.4, 0.3)^T$ are randomly considered as two general strategies. The simulation results are shown in Figure 6. The simulation results show that the supervision probability of the public would gradually rise, while the complying probability of OC and regulation probability of GS fluctuate repeatedly. Compared with fluctuations of the strategy selections of OC and GS in Figure 6a, the fluctuation of the strategy selections of OC and GS in Figure 6b is more significant, indicating that the initial strategy ES_{g2} is capable of greater potential risk and resource waste.

In summary, the simulation results show that the three stakeholders' strategy selections repeatedly fluctuate, which demonstrates that the evolutionary stability strategy does not exist in multi-player long-term dynamic gameplay. Moreover, such strategy instability undoubtedly increases the possibility of risk and resource waste in the safety regulation of MIPs, which should be avoided in daily management.

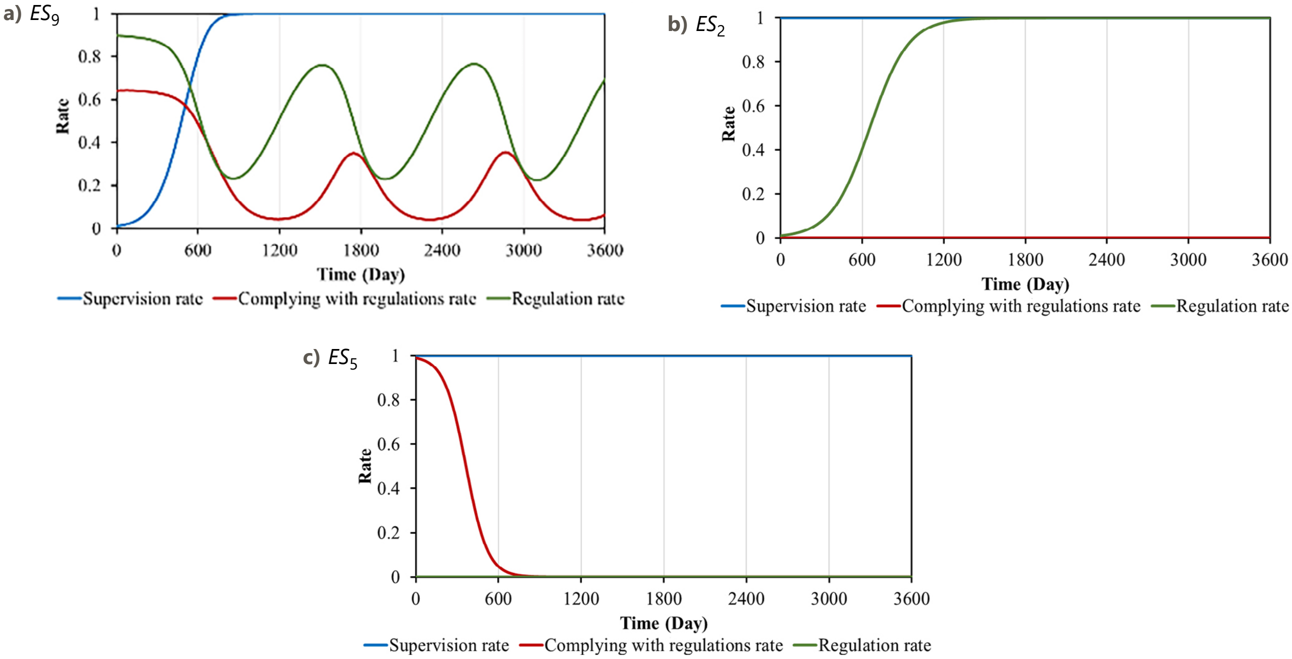


Figure 5. Evolutionary game results under the existing mutation

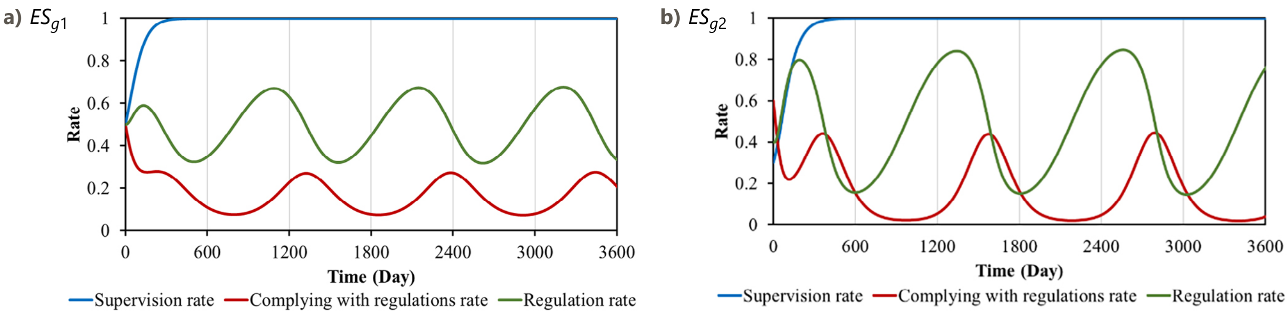


Figure 6. Evolutionary game results under the random initial strategies

4.3. Stability analysis on strategy simulation under different penalty and incentive scenarios

To find the evolutionary stability strategy, taking different penalties or incentives is a common way (Wang et al., 2019; Zeng et al., 2019; Zhu et al., 2020b). Upon which to motivate OC to comply with the regulations in the safety regulation of MIPs, and to examine the impact of different penalties or incentives on safety regulation, this research conducts simulations by varying the penalties or incentives for revealing the impact mechanism, i.e., different penalty scenarios, different compensation coefficient scenarios, and different public rewards scenarios.

4.3.1. Different penalty scenarios

In the multi-player game SD model for safety regulation of MIPs, the penalty of OC to circumvent the regulations changes from 5 to 3, 4, 6, and 7. For the initial strategy ES_{g1}, the simulation results of the multi-player game are shown in Figure 7. The detailed analysis of those results is as follows.

In Figure 7, it is apparent that there are thresholds of penalty between 3 and 4 and between 6 and 7 that can keep the results in stabilization, which can be calculated by Eqn (13), and when the value of penalty is lower than the threshold between 3 and 4, the stabilization state is constant same as in Figure 7a, and when the value of penalty is higher than the threshold between 6 and 7, the stabilization state is constant same as in Figure 7d. Figure 7 and Figure 6a show that as penalties increase, the OC gradually strengthens safety management by complying with the regulations, while the GS gradually reduces the execution of regulation duties. When the penalty is 3 (as shown in Figure 7a), the best strategic selection for the OC is to circumvent the regulations, which will provide great potential risks to society. Therefore, a penalty of 3 is not appropriate. On the contrary, the OC chooses to perform safety management by complying with the regulations when the penalty is 7 (as shown in Figure 7d). However, this may lay hidden trouble for the enthusiasm and sustainable development of the OC's safety management due to high management stress and tension over time. For the penalty set to 4 in Figure 7b and 6 in Figure 7c, the strategy selections of OC and GS are still in constant fluctuation, causing uncertainty and uncontrollable situations during the operation of MIPs.

4.3.2. Different compensation coefficient scenarios

In the multi-player game SD model for safety regulation of MIPs, the compensation coefficient changes from 0.4 to 0.2, 0.3, 0.5, and 0.6. For the initial strategy ES_{g1}, the simulation results of the multi-player game are shown in Figure 8. The detailed analysis of those results is as follows.

From Figures 8b, 8c, 8d and Figure 6a, it is apparent that as the compensation coefficient increases, the possibility of the GS's executing regulation duties gradually decreases, while the possibility of the OC complying with the regulations rises than zero, accompanied by a gradual increase in the frequency of fluctuations, which cannot effectively prevent risks. Specifically, as the compensation coefficient increases, the GS becomes slower to respond to the inappropriate behavior of the OC because the compensation policies would objectively increase the GS's cost of safety regulation. Accordingly, OC will further respond

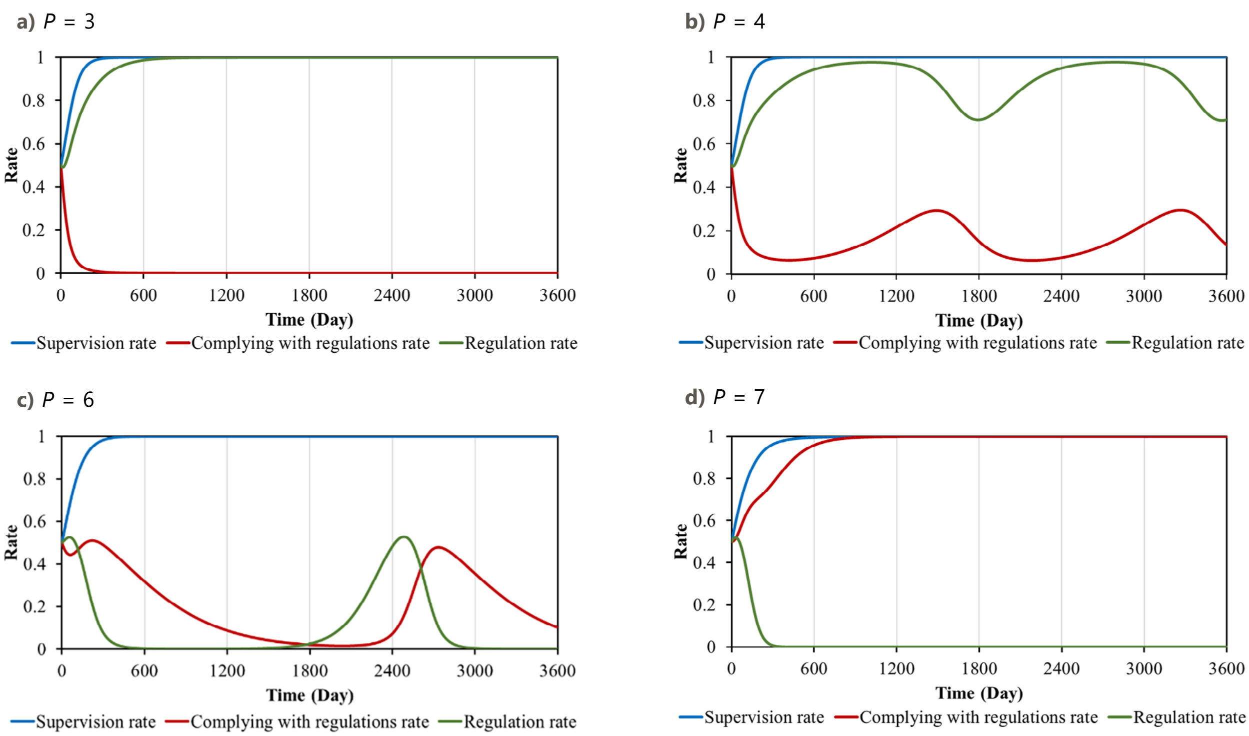


Figure 7. Evolutionary game results under different penalties

to GS's strategy to maximize profit. The simulation results are in line with reality, because the OC's response generally lags behind the GS's strategy in practice. In Figure 8a, when the compensation coefficient θ is set as 0.2, the GS and public's strategy selection gradually evolves to 1, while the strategy selection of OC gradually moves towards 0, indicating that the compensation effect has failed, which is a regulatory failure in the safety management of MIPs.

4.3.3. Different public rewards scenarios

In the multi-player game SD model for safety regulation of MIPs, the public rewards change from 0.7 to 0.3, 0.5, 0.9, and 1.1. For the initial strategy ES_{g1}, the simulation results of the multi-player game are shown in Figure 9. The detailed analysis of those results is as follows.

Figure 9 and Figure 6a suggest that the changes in public rewards cannot prevent the fluctuations in the safety

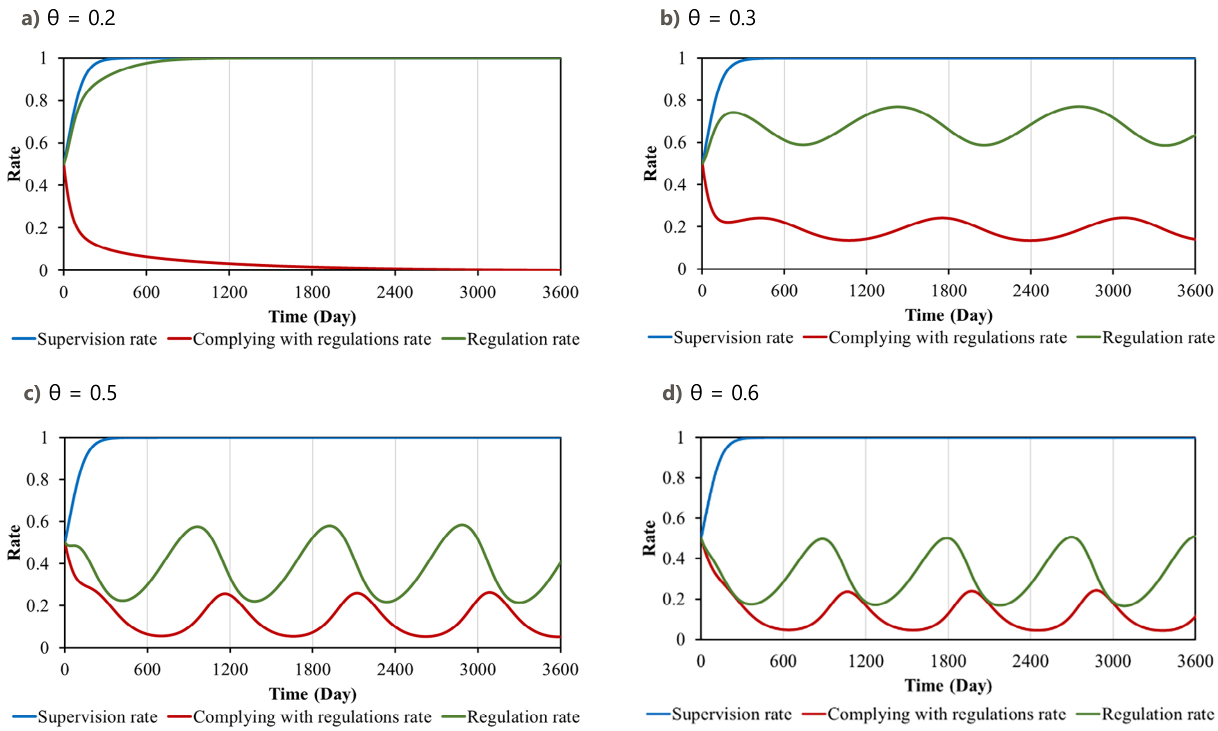


Figure 8. Evolutionary game results under different compensation coefficients

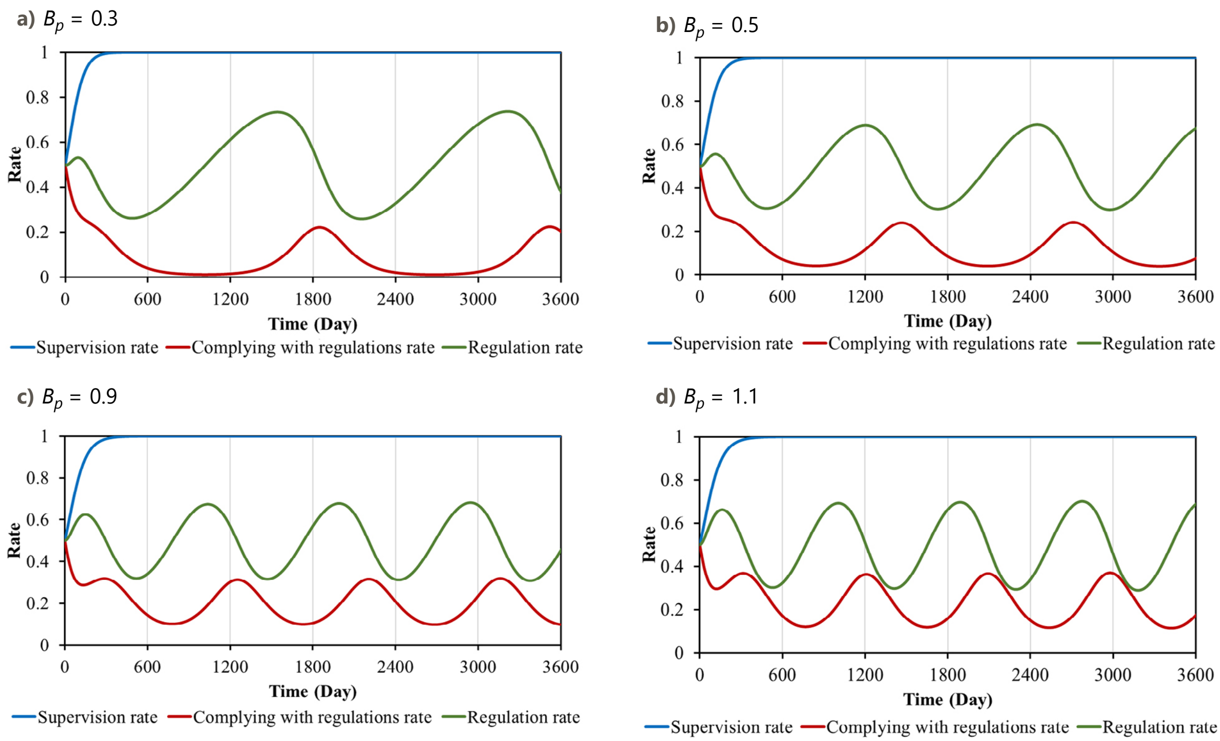


Figure 9. Evolutionary game results under different public rewards

regulation of MIPs. As public rewards increase, the possibility of the OC complying with the regulations gradually rises, and the amplitude and frequency of fluctuations increase accordingly. Although public rewards played a small role in this scenario, it also provides at least some exploration of strategy choice and policymaking. In addition, the simulation results show that changing the public rewards cannot achieve the strategic stability of the three stakeholders, indicating that risks still exist in the operation of MIPs.

In general, the SD model can intuitively analyze the dynamic evolution process of the three-player game for safety regulation of MIPs and reveal the influence of different safety regulation factors. In the multi-player game SD model for safety regulation of MIPs, no appropriate strategy can be adopted regardless of the penalties, compensation, and rewards. Although high penalties can achieve a stable strategy, it is not suitable for the long-term sustainable development of MIPs due to the high management stress and tension imposed on managers. In addition, the common situation is that the OC and GS have an alternating push-pull relationship, but such an uncertain process for the safety regulation of MIPs can waste resources and provide the potential for risks. Therefore, further exploration is needed to obtain stable strategies and prevent risks.

4.4. Stability analysis on strategy simulation under dynamic penalty scenarios

In view of the above stability analysis on strategy simulation under different penalty and incentive scenarios, adjusting the fluctuation by changing the penalty is quite effective, but is failing in finding the evolutionary stability strategy. Many previous studies have proved that fluctuations can be effectively restrained by associating penalties with the ratio of irrational behavior, i.e., by employing a dynamic strategy (Feng et al., 2020; Liu et al., 2015; Wang et al., 2011). In line with that, the dynamic penalty strategy is proposed in this research to explore an effective way for restraining the fluctuations. The dynamic penalty strategy can be expressed as follows:

$$P' = (1 - x)P, \tag{14}$$

where P' represents the dynamic penalty strategy in the safety regulation of MIPs, which is related to the probability of circumventing the regulation, that is to say, the higher the probability of circumventing the regulation, the higher the penalty for the OC. The new system flow diagram is presented in Figure 10, which is changed from Figure 3 based on Eqn. (14) to explore the evolutionary stability strategy. Compared to Figure 3, the changes are labeled in Figure 10 with a yellow dashed box.

For analyzing the strategic stability of multi-player games under the dynamic penalty scenario, the random initial strategies ES_{g1} and ES_{g2} are considered. The simulation game results are shown in Figure 11, which is analyzed in detail as follows.

Compared to Figure 6, it can be seen in Figure 11 that the strategies of GS, OS, and public are smoother and more stable, and their evolutionary game process converges to a stable state around $S = (0.156, 0.801, 1)$, indicating that the dynamic penalty strategy effectively restrains the fluctuations in the multi-player game on the safety regulation of MIPs.

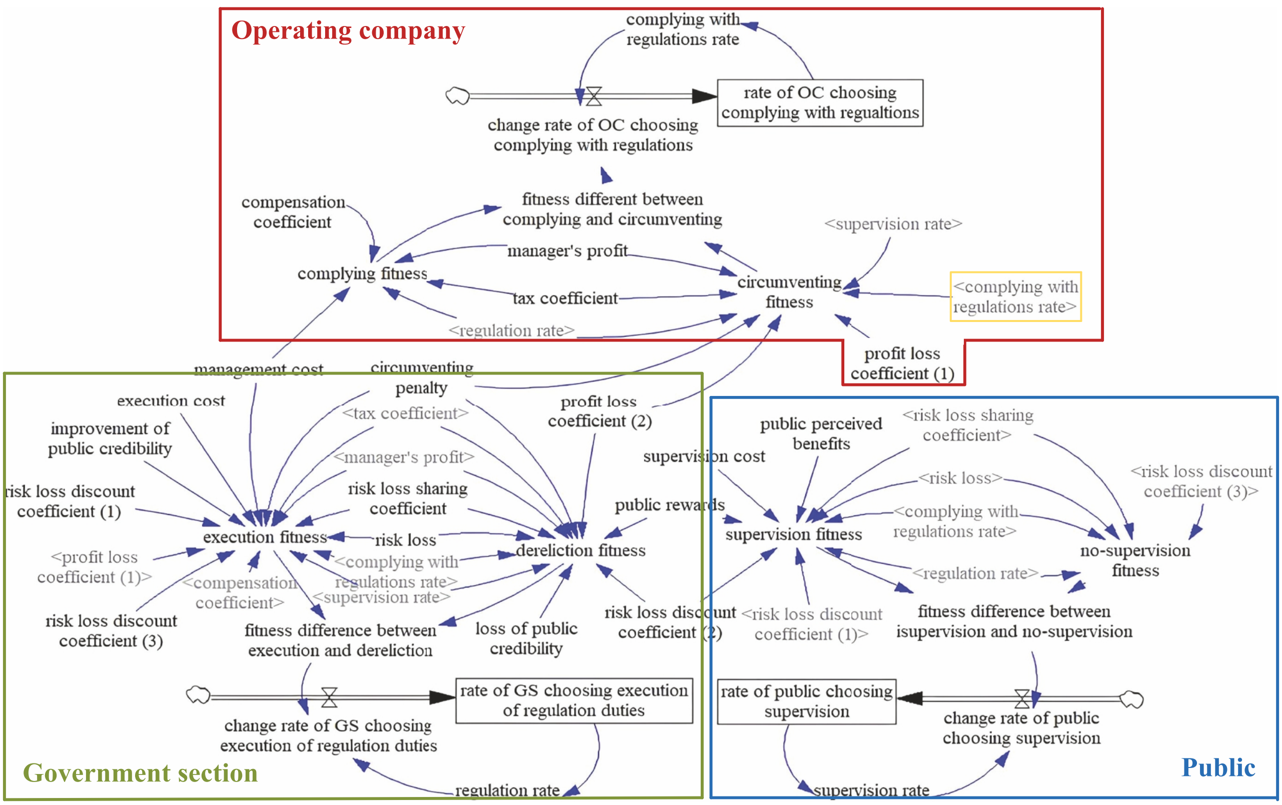


Figure 10. Evolutionary game with the SD model under the dynamic penalty scenario

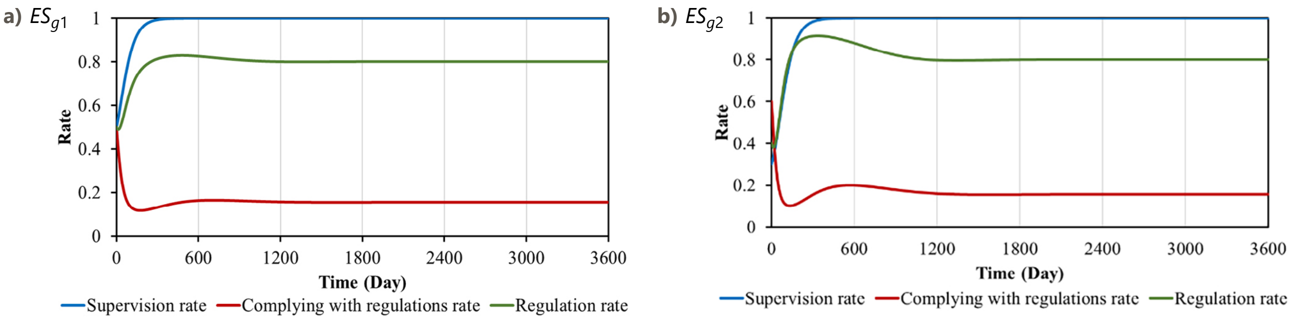


Figure 11. Evolutionary game results under the random initial strategies with the dynamic penalty

Moreover, the stable state is not affected by the initial strategies. For examining the stable state is the evolutionary stability strategy, the Jacobian matrix of the game is computed as follows:

$$J = \begin{bmatrix} -475/721 & 1717/5099 & 493/2719 \\ -695/969 & 0 & 0 \\ 0 & 0 & -579/4222 \end{bmatrix}. \quad (15)$$

Then, the eigenvalues are calculated as follows:

$$\lambda_{1,2} = -\frac{475}{1442} \pm \frac{3786}{10381} i,\ \lambda_3 = -\frac{579}{4222}.$$

Since those eigenvalues are negative, the stable state is an evolutionary stability strategy. However, it is noted that employing dynamic penalty scenarios can result in a stable but optimal strategy because OC and GS do not completely comply with the regulation and completely execute the regulation causing potential risks.

In summary, the dynamic penalty strategy can effectively restrain fluctuations in multi-player games on the safety regulation of MIPs and reach the evolutionary stability strategy to reduce the safety risks caused by uncertainty. However, OC and GS do not completely implement the corresponding regulation strategy and complying with the regulations, which has uncertainty and risks, so that the probabilities of safety regulation conducted by the OC and GS need to be further improved to reduce the risks.

4.5. Stability analysis and check under the optimal dynamic penalty-incentive scenario

In the multi-player game on the safety regulation of MIPs, ensuring the OC complies with the regulations is a significant objective. Aiming at the situation that OC has a low probability of complying with the regulations driven by the pursuit of profit with providing great potential for risks, the stable state around S = (0.156, 0.801, 1) is not the ideal evolutionary stability strategy. Thus, effective strategy selection and stability analysis need further exploration. According to the analysis of the compensation coefficient and public rewards, it is evident that they can also influence the stakeholders' strategic selections. Fully considering the dynamic penalty, compensation coefficient, and public rewards, this research proposes the dynamic penalty-incentive strategy for exploration. The dynamic compensation and public rewards can be expressed, respectively, as follows:

$$P'' = (1 - x)P + (z + y)c_a,\ C_d' = x(\theta c_a),$$
$$B_p' = zB_p,\ T_g' = yT_g,\ S_g' = (1 - y)S_g,\ PB' = zPB, \quad (16)$$

where P'' represents the dynamic penalty strategy; C_d' is the dynamic compensation; T_g' and S_g' refer to the dynamic improvement of public credibility and loss of public credibility, respectively; PB' stands for the public's perceived benefits. These are designed to enhance safety regulation among these stakeholders, including dynamically adjusting penalties and incentives, which are related to the probability of the OC complying with regulation, the probability of GS executing the regulations, and the probability of public performing supervision, respectively. The new system flow diagram is depicted in Figure 12, which is changed from Figure 3 based on Eqn (16) to explore the evolutionary stability strategy. Compared to Figure 3, the changes are labeled in Figure 12 with a yellow dashed box.

For analyzing the strategic stability of multi-player games under the dynamic penalty-incentive scenario, the random initial strategies ES_{g1} and ES_{g2} are considered. The simulation game results are shown in Figure 13, which is analyzed in detail as follows.

Compared to Figures 6 and 11, it is clear from Figure 13 that the strategies of GS, OC, and public are smoother and more stable, and their evolutionary game process converges to a stable state S^* = (1, 0, 1), in which the OC will nearly choose to comply with the regulations as the optimal strategy, while the public will nearly choose to supervise the OC as the optimal strategy, and GS will nearly choose dereliction of regulation duties as the optimal strategy, which can save costs. The simulation results show that the dynamic penalty-incentive strategies can not only effectively restrain the fluctuations in the multi-player game on the safety regulation of MIPs, but also provide a stable state, which is not affected by the initial strategies.

For examining the stable state is the evolutionary stability strategy, the Jacobian matrix of the game is computed as follows:

$$J = \begin{bmatrix} -706/963 & 0 & 0 \\ 0 & -19/5 & 0 \\ 0 & 0 & -1/2 \end{bmatrix}. \quad (17)$$

Then the eigenvalues are calculated as follows:

$$\lambda_1 = -\frac{706}{963},\ \lambda_2 = -\frac{19}{5},\ \lambda_3 = -\frac{1}{2}.$$

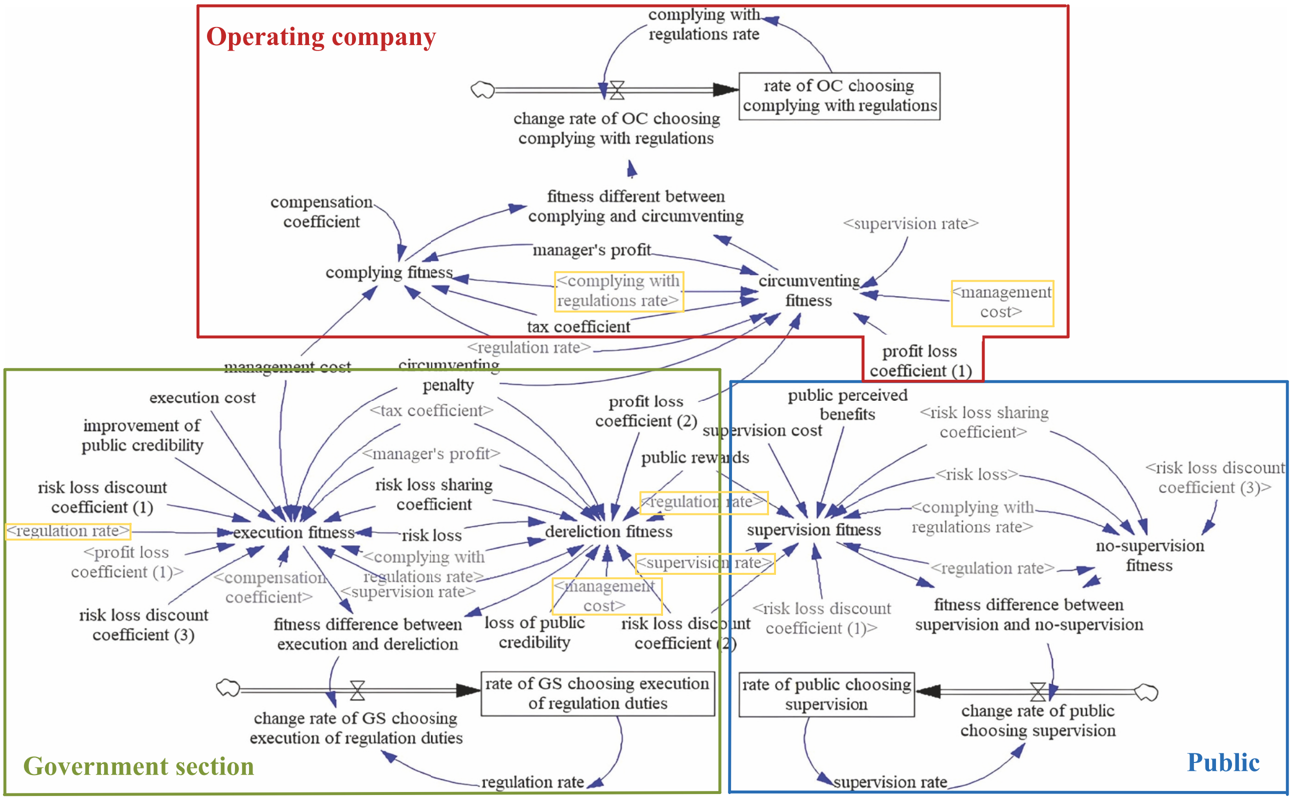


Figure 12. Evolutionary game with the SD model under the dynamic penalty-incentive scenario

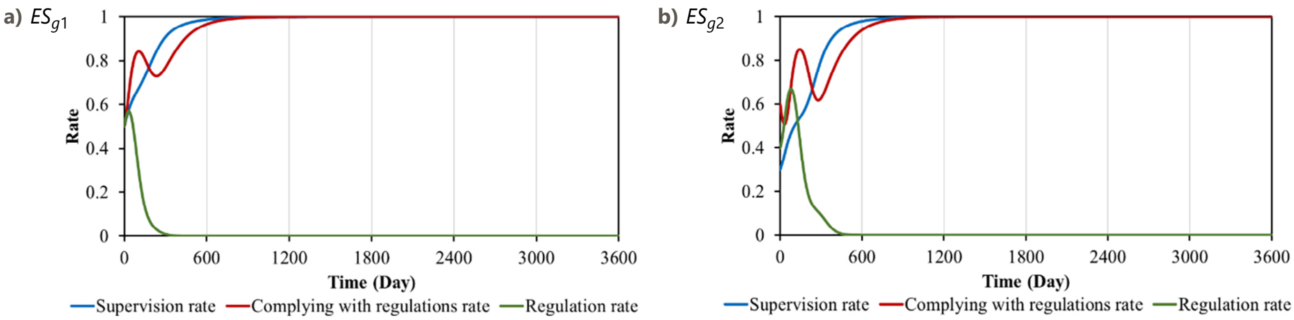


Figure 13. Evolutionary game results under the random initial strategies with the dynamic penalty incentive

Therefore, the S^* = (1, 0, 1) is the evolutionary stable strategy. It is noted that adopting the dynamic penalty-incentive scenario can obtain the optimal strategy because the participating stakeholders are fully engaged in the execution of the corresponding strategy with the steady state, which is not affected by the initial strategies.

In conclusion, the dynamic penalty-incentive strategy can not only effectively restrain fluctuations of the strategy selection in multi-player game on the safety regulation of MIPs, but also can provide the ideal evolutionary stability strategy, in which the OC will nearly choose to comply with the regulations as the optimal strategy while the public will nearly choose to supervise the OC as the optimal strategy, and GS will nearly choose dereliction of regulation duties as the optimal strategy, which can save costs. Additionally in this scenario, risks can be effectively prevented, which means the operational safety of MIPs is improved.

5. Discussion

This research explores the safety regulation strategy in MIPs based on the evolutionary game and SD for ensuring the safe operation of MIPs, where the evolutionary game is applied to describe the interactions of multi-player games in the safety regulation of MIPs under bounded rationality, while the SD is adopted to analyze the dynamic process and stability of game equilibrium and the implementation effect of different strategy simulation scenarios. In the different penalty and incentive scenarios, the existing repeated fluctuations make it difficult to develop effective safety regulation strategies, resulting in the potential for risks and resource waste. In view of the analysis of different penalty scenarios, the OC is likely to choose to circumvent safety regulations without penalties or penalties being low, which is not an appropriate strategy for management. According to the analysis of different compensation coefficient scenarios and different public rewards scenarios, the OC may tend not to comply with the regulations without the GS incentive, the GS, thus, should motivate the OC and the public by providing some compensation and rewards, respectively. Although excessive penalties can restrain fluctuations, blindly increasing the penalties cannot result in a better implementation effect, and conversely, it may cause trouble for the enthusiasm and sustainable development of the OC's safety management due to high management stress and tension over time, thus increasing the cost of regulation uneconomically.

In view of the above-mentioned analysis, a good strategy for the safety regulation of MIPs cannot simply impose penalties or incentives to improve the probability of safe operation of MIPs. Upon that, this research conducts further explorations of dynamic penalties that can effectively restrain fluctuations, but risks still exist. Moreover, the dynamic penalty-incentive scenario can provide the optimal strategy to conduct safety regulation in the operation of MIPs, in which the OC nearly chooses to comply with the regulations as the optimal strategy, while the public nearly chooses strict execution of regulation duties as the optimal strategy. The simulation results indicate the effectiveness of public supervision and dynamic penalty-incentive strategies in the safety regulation of MIPs. Owing to the insufficient regulatory practitioners in practice, carrying out comprehensive regulation by GS is unrealistic and impossible, resulting in the implementation of safety regulations falling far from the expected requirements. This issue can be alleviated by the public, as beneficiaries and taxpayers, who can disclose the information about the safety regulation of MIPs to the GS with low cost, thus, encouraging the public to supervise the OC actively is significant to ensuring safety regulations of MIPs. On the other hand, encouraging public participation can mobilize social vitality to further promote social development. However, this does not mean that the overall credibility of GS will be low, which also depends on other factors, such as social welfare.

The established multi-player game SD model for safety regulation of MIPs offers a scientifically comprehensive tool to handle the safety operation problem of MIPs, which can prevent risks as much as possible and present a win-win situation for the efficient and safe operation of MIPs. In light of the result analysis, several managerial implications can be outlined as follows: (1) the complex interactions among stakeholders in the safety regulation of MIPs are considered into mathematical models for developing satisfactory safety regulation strategies; (2) the established multi-player game SD model for safety regulation of MIPs can facilitate the understanding of the game among the OC, GS, and public. Simultaneously, the model has the ability to analyze the simulation process over the long-term operation; (3) the penalty-incentive mechanism is adopted to conduct an in-depth analysis of safety regulation of MIPs, providing ways to gain insight into operational mechanisms of MIPs and contributing to the GS to put forward policies for guiding the safe operation of MIPs; (4) the integration of the evolutionary game and SD is an effective way to obtain ESs and conduct stability analysis of game equilibrium. In addition, the model serves as a good modeling example that can be extended to many other similar management areas, such as tunnel construction, engineering construction energy consumption, nuclear energy operation, etc. with minor modifications. To better serve the practice, in accordance with the above detailed analysis results of different scenarios, when using this model, the dynamic penalty-incentive scenario can be directly used to analyze different feature situations for obtaining the optimal regulation strategy.

6. Conclusions and future works

This research presents a novel model integrating the evolutionary game and SD to analyze the multi-player game process affecting the safety regulation of MIPs with different strategies and to explore the decision-making mechanisms of different stakeholders in the safety regulation of MIPs, where, the evolutionary game is used to describe the long-term interactions of stakeholders based on the tripartite evolutionary game model, then SD is adopted to analyze the effects of different strategies on ESs and stability of game equilibrium. To obtain the stable ES, this research explores five scenarios to validate the effectiveness of the model. This model provides a way to model and simulate the interactions and strategic choices for safety regulation of major projects, which can serve as an important reference to achieve the desired results.

In view of the results, the individual roles and their interactions among GS, OC, and public are analyzed in detail and upon which the game model and replicated dynamics equation are constructed based on a comprehensive consideration of the influence factors to model them, followed by using SD to analysis, the probability of safe operation of the MIP cannot be effectively increased by simply imposing penalties or incentives, while dynamic penalties can effectively restrain fluctuations, but the risks still exist; instead the dynamic penalty-incentive strategies can not only effectively restrain the fluctuations of the strategy selection, but also provide an ideal evolutionary stable strategy, in which the OC could nearly choose safety management by complying with the regulations, while the public could nearly choose to supervise the OC as their optimal strategy to prevent risks. Accordingly, the proposed method has great potential to serve as a tool to identify reasonable regulatory strategies for practical application.

The proposed method is capable of providing positive results, nevertheless, some interesting extensions remain that may be potentially useful for future research. First, we assume that the profit of OC remains constant throughout the simulation period. In general, the profit of OC varies from year to year, so the profit variation should be considered in future studies. Meanwhile, since the regulation cost of the GS and the supervision cost of the public decrease with the development of technology, it is desirable to set the cost differently with the development of technology.

Second, this research only considers rewards and penalties as policy interventions. In fact, the operation of OC is interfered by numerous factors, such as environmental protection policies, internal organizational relationships, and supply chains, among others, which may affect the behavior of OC. To better analyze the existence, these factors should be considered. Third, this research only considered three key stakeholders, namely the GS, OC, and the public, while ignoring other stakeholders such as suppliers. In the subsequent study, more stakeholders will be considered for inclusion in the evolutionary game model. Fourth, this research only considered the external factors of OC, and the internal environmental factors can also be studied to extend the research on regulation. These considerations can contribute to the validity and reliability of the modeling and simulation to deepen the understanding of the influencing mechanisms of safety regulation of MIPs. Furthermore, analyzing different penalty and incentive scenarios may yield varied effects, but the underlying reasons are not deeply explored. Moreover, extending the application of the proposed method by minor modifications to other areas, such as tunnel construction, engineering construction energy consumption, nuclear energy operation, etc., is a practical and valuable direction that warrants devotion. For example, in the case of tunnel construction, the interaction between the management company, the government, and the public can be analyzed to develop management strategies or the relationship between different organizations within the company can be analyzed to develop operational strategies.

Acknowledgements

This research was supported by the National Natural Science Foundation of China (NSFC) (No. 72301233) and the National Social Science Fund of China (No. 18ZDA043).

Disclosure statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in the manuscript.

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