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Developing a Construction Safety Standard System to Enhance Safety Supervision Efficiency in China: A Theoretical Simulation of the Evolutionary Game Process

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Abstract: Labor safety is one of the most fundamental indicators to improve contractors' sustainability. Safety supervision plays a crucial role in affecting the safety performance of infrastructure projects. However, studies of standards development to enhance safety supervision efficiency are far from complete. Safety standards define safe behaviors for construction workers and hazard control processes in the workplace, and they are usually considered as an important part of safety control. In addition, the systematic reform of construction safety standards in China provides an innovative perspective to enhance safety supervision efficiency by linking standards to supervision. For this purpose, this paper proposes the concept and framework of the "Construction Safety Standard System (CSSS)" through expert interviews. CSSS hierarchically classifies safety standards and integrates similar standards. Its implementation will significantly influence the behavioral decisions of safety supervision stakeholders. Evolutionary game (EG) theory is applied to demonstrate the decision-making procedure in CSSS establishment and application. Furthermore, system dynamics (SD) is utilized to model and analyze equilibrium states under different supervision strategies. Meanwhile, case studies are implemented to assess the CSSS's effectiveness in reality. The numerical results indicate that through CSSS implementation, the strategy choice fluctuation of supervisors and contractors is suppressed and a more desirable stable equilibrium is reached. The government tends to supervise and contractors tend to obey safety standards consciously. The findings reveal that CSSS can enhance safety supervision efficiency and have meaningful implications for theoretical study on safety supervision and construction safety management practice.

Keywords: safety standards; Construction Safety Standards System (CSSS); safety supervision; evolutionary game (EG) theory; system dynamics (SD)

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1. Introduction

The construction industry is regarded as one of the riskiest fields, mainly since laborers are exposed to a changeable workplace that contains heavy equipment, noise, and other serious hazards [1]. It employs approximately 7% of global workforce, nevertheless, about 100,000 workers die on construction sites each year, which accounts for approximately 35% of global professional fatalities [2–4]. In South Korea, the United Kingdom, and the USA, fatalities related to construction account for 27.6%, 27.2%, and 20% of all professional fatalities, respectively [5,6]. In China, the proportion of fatalities in the construction industry is far above other industries [7,8]. When a safety accident occurs, it attracts the attention of the whole society since the construction industry is intimately associated with the lives of the general public. Fatalities have a detrimental influence on contractors' competitiveness since they cause not only financial loss but also loss of life [9,10]. The lack development of contractor safety standards will seriously hinder the healthy development of the whole industry. As a result, it is crucial to improve the safety performance of infrastructure projects [11]. Previous research has demonstrated that safety standards play a major role in defining the safe behavior of workers, controlling hazards in the workplace, diminishing the number of fatalities, and improving the safety performance of infrastructure projects [12].

Additionally, there are growing appeals for improving safety supervision [13–16]. Theories of construction safety supervision are, however, focused on explaining how to regularly inspect and evaluate the safety condition of the contractors' construction sites [14]. In studies of other industries, penalties have been widely considered to be a good way to enhance safety supervision efficiency [15–19].

Only a few studies focus on the role of standards in safety supervision [20–22]. A standard is a normative instrument that is jointly developed by the people or representatives, adopted by consensus, and observed by all members of the group together. Safety standards are often seen as a vital part of security control [23]. However, the role of safety standards in safety supervision is still not complete in China.

There are two fundamental issues with the application of safety standards in China. First, many standards are not adequately implemented [24]. Second, some standards have fallen behind the development of the industry [25]. Safety standards define safe behaviors and safe control strategies to control workplace hazards, yet governmental supervision authorities (GSA) often focus on major items, such as scaffolding, construction elevators, and crane operations [26]. Other items that may cause safety hazards are rarely listed in regulation content. In addition, inconsistent regulatory guidelines in different regions have led to different construction safety standards (CSS) and inefficient management of construction contractors. More seriously, some standards are not operational. Nevertheless, self-regulation of contractors cannot control safety risks. As contractors pursue profit maximization, they place a greater emphasis on the final value of construction products and pay insufficient attention to safety issues. Therefore, contractors are motivated to take chances and disregard the application of CSS to keep the construction project on schedule [27,28].

Therefore, it is important to solve the problems of CSS application. Although previous studies have suggested the concept of a "construction standard system" [29,30], a safety-related standard system has rarely been studied directly. Some studies suggested enhancing construction safety supervision efficiency from the perspective of the government or made recommendations for standardizing safety production management from the standpoint of contractors [31,32]. Nevertheless, CSS application issues are the interaction of multiple factors rather than one type of standard or standard-related party, such as the government or contractors, unilaterally. One approach to address this issue involves evolutionary game (EG) theory, which has been generally accepted in the area of construction safety supervision by modeling decision-making procedures. However, existing studies have mostly concentrated on modeling the game procedure between two players [33] and rarely have focused on multiplayer game situations.

This research seeks to solve two problems: (1) how to unify the CSS of supervision and safety production to improve CSS integration and operability; and (2) how to analyze standard stakeholders' decision-making interactions and identify behavioral characteristics to theoretically verify the effectiveness of CSSS for safety supervision. Given this, this study proposes a "Construction Safety Standards System (CSSS)" and designs a prototype of a "Construction Safety Standards System Table (CSSST)" to achieve the unification of CSS. A multiplayer EG model is constructed and system dynamics (SD) simulation is used to validate the role of CSSS in enhancing safety supervision efficiency. To assess the CSSS's effectiveness in real-world scenarios, we implemented case studies.

The main outcomes of this research are as follows: (1) the prototype of CSSST has been established and its critical role in enhancing the safety supervision efficiency has been validated; (2) the introduction of CSSST has resulted in a tripartite game of standard management authorities (SMA), GSA, and contractors. The collaboration of EG and SD simulation resolves the problem of multiplayer interrelation, which has seldom been implemented in existing research.

2. Literature Review

Studies have shown that safety supervision is a game procedure, so we can adopt game theory to investigate safety supervision issues [34–37]. With the rapid development of game theory, EG theory has increasingly developed into a practical method for analyzing decision-making behavior [34–38].

The core thought of EG theory is that the stakeholders play repetitive games in a system [34]. EG theory is premised on the hypothesis of limited rational players, which means each player cannot achieve the ideal solution in every game, and they will change strategy dynamically [39]. To further research the game equilibrium state, replicator dynamics was proposed to describe the strategy's probability in a system [35]. The game equilibrium state is reached when the increased proportion of the replication dynamics is zero [35]. Additionally, to describe a stable game equilibrium state, Evolutionary Stable Strategy (ESS) was proposed [39]. If ESS exists, the probability of a particular strategy will remain constant [39]. In the process of reaching ESS, each player's behavior is influenced by other players' current strategies [39]. Therefore, it is important to identify participants and available strategies. EG considers the limited reasonability of players and players can adjust their strategies, which is more in agreement with real management situations. Supervisors and contractors create conflicts of interest due to the different requirements and goals [16]. They behave as limited rational stakeholders due to the difficulty of problems or cognitive limitations [40]. They regulate strategies dynamically to optimize their income by observing and comparing payoffs. Therefore, interactions between supervisors and contractors can be seen as a dynamic game process [40].

Most of the existing research focuses on the dual supervision game. For example, Hausken and Zhuang [41,42] utilized game theory to model the game process between enterprise and governmental supervisors. Chen et al. [43] adopted the EG model to investigate the game process between developers and governmental supervisors. Analogous studies have been implemented by Zhou et al. [44], Liu et al. [45], Cheng and Chen [40], Cao and Wang [46], Liu et al. [47], Shan et al. [48], Yu et al. [49], and Feng et al. [50]. In addition, the game equilibrium state of the dual supervision game will be affected by a few factors such as contractors' safety efforts, penalties for failing to comply with standards, benefits of safety measure adoption to society and contractors, GSA investments and benefits, and penalties for GSA when the supervision is not performed [47–50]. The cyclical fluctuation phenomenon appears in safety supervision [47–50]. The initial state of game players and the income of various strategies are the two principal factors of the fluctuation occurrence [47–50].

However, with the introduction of CSSST, SMA joined the evolutionary game process between GSA and contractors. Compared to the two-party evolutionary game, the game equilibrium state of the three-party evolutionary game is more complex [51]. In addition, EG theory has its limits when it comes to showing the way to equilibrium [52]. Some scholars pointed out SD can be adapted to analyze the equilibrium solutions of the multiplayer evolutionary games [53]. SD combines qualitative and quantitative analysis to study the interactions and behavior of complex systems through simulation [54]. It does not pursue the "best solution" but rather looks for solutions to improve system behavior by observing the overall situation [50]. Existing studies have utilized SD to analyze multiplayers' equilibrium points, such as safety regulation [53], railroad supervision [50], and construction behavior safety [55].

In sum, there are two central gaps in previous studies. First, standards play an important role in safety supervision. However, how to formulate a unified safety standard and implement it mostly stay at the level of opinions and suggestions, and no new tools have been introduced to maximize the role of safety standards. Second, previous research mostly concentrates on the interaction between GSA and contractors in the evolutionary game, while there is less research considering the participation of SMA. Therefore, this paper proposes a new tool for enhancing safety supervision efficiency: CSSST. The concept of CSSST will be introduced in detail in the next section. Under the guidance of CSSST, contractors will have a better understanding of what should and should not be done on construction sites at lower costs, and governmental supervisors will be less burdened with work. As for the research method, this study appropriately adopts EG theory to study the stable strategy among SMA, GSA, and contractors. SD is used to model EG procedure of supervision. The collaboration of these two approaches helps to explain the different outcomes of each strategy and to identify the key factors in the implementation of CSSST.

3. Methodology

3.1. Overall Research Framework

We adopt a four-step research methodology as follows: (1) presenting the concept of CSSS and designing the prototype of CSSST and the CSSS feedback platform, (2) designing a multiplayer evolutionary game model and using system dynamics simulation, (3) conducting numerical experiments and the related analysis to validate the important role of CSSS in improving safety performance, and (4) verifying the effectiveness of CSSS in a real-world by conducting case studies. Figure 1 depicts the overall research framework.

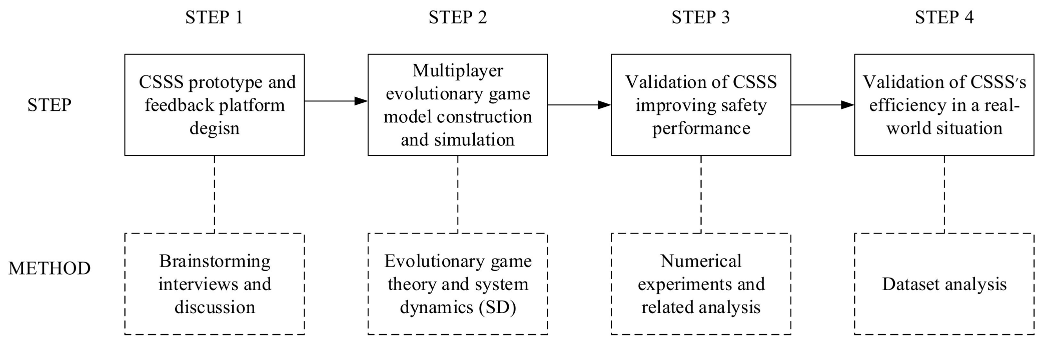

Figure 1. Overall research framework.

3.2. CSSS and the CSSS Feedback Platform

CSSS is an innovative method that has not been widely used in safety supervision, expert group interviews are employed to discuss the concept of CSSS, the prototype of CSSST, and the CSSS feedback platform, as this is a good way to propose innovative ideas by utilizing the wisdom of the expert group [56], We had brainstorming meetings with an expert panel of twenty-five construction safety experts. Moreover, the expert group consisted of eight security professionals, ten safety managers of contracted projects, four experts from the China Construction Safety Association, and three scholars from diverse and geographically dispersed organizations in China. The team members had over ten years of safety management experience. The certificates of these experts agree with the previous research [1].

The research team formed two subcommittees to conduct research: (1) the concept of CSSS and the prototype of CSSST; (2) the CSSS feedback platform and the implementation flow of the CSSS feedback platform. To ensure the consistency of the results, two subcommittees reported weekly to the entire research group. The following two subsections present the results of the expert group interviews.

3.2.1. The Concept of CSSS and the Prototype of CSSST

Previous studies have suggested the "construction standard system" and highlighted its importance in ensuring the sustainable development of the construction industry [29,30]. CSSS will also improve the safety performance of infrastructure projects, reduce safety supervision costs, enhance safety supervision efficiency, and promote the sustainability of the construction industry [57]. CSSS is defined as a scientific and organic system of documents formed by CSS according to their internal links. CSSST refers to a set of well-organized content tables of CSS. Other countries can utilize the same guidelines and methods to establish a system of CSS suitable for their national conditions. Through this work, we aim to accomplish systematic management of CSS.

CSSS is divided into three levels, which are Basic Standards (BS), General Standards (GS), and Specialized Standards (SS). BS are the basis for the development of the other standards in CSSS. According to the content, BS are divided into terminology standards, classification standards, and logo standards. BS strive to cover and unify the definitions and concepts that GS and SS may involve. GS refer to unified standards applicable to a certain stage or certain matter of construction, such as risk identification and electricity use. SS refer to management or technical standards applicable to specific objects, entities, and processes. SS and GS have a uniform structure. The structure of CSSS is shown in Figure 2.

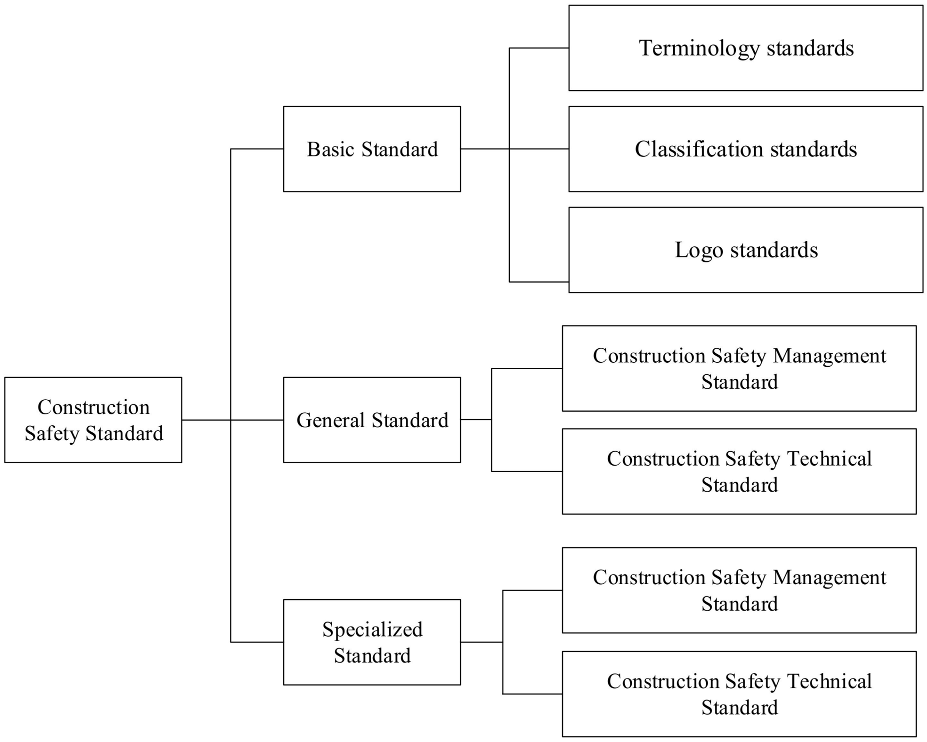

Figure 2. Structure of CSSS.

3.2.2. The CSSS Feedback Platform and the Implementation Flow of the CSSS Feedback Platform

Based on the framework of CSSS, we designed a CSSS feedback platform. The platform provides structured forms to collect contractors' feedback information on CSS usage. Thus, GSA and SMA have timely access to related information of CSS errors, questions about CSS, and contractors' comments on CSS. This platform combines CSSS development and safety supervision. Given this, GSA can adjust their supervision strategies to control safety in the construction industry, and SMA can update their standard development plan to meet the needs of contractors. The implementation flow schematic of the CSSS Feedback Platform is illustrated in Figure 3.

As shown in Figure 3, the implementation flow of the CSSS feedback platform includes four steps: (1) CSS formulation; this process mainly involves the participation of SMA and GSA. SMA focus on the development and management of the entire process of CSS, while GSA focus on standard operability. SMA are responsible for the CSS project approval. GSA and SMA need to form a joint force to cultivate a sustainable standard development team with professional capabilities. In addition, GSA and SMA are responsible for CSS publicity and training. The CSS project approval, compilation, review, publicity, and training should be based on a unified CSSS framework. (2) CSS application; this process involves the participation of GSA and contractors. CSSS also serves as a prerequisite in CSS application. Specifically, contractors should strengthen daily supervision of CSS implementation in compliance with the contract. GSA implement hierarchical supervision according to CSSS. (3) CSS application feedback; this process involves the participation of contractors. The

CSSS feedback platform provides a structured standard usage feedback form to facilitate the collection of standard errors and questions. Thus, GSA and SMA have timely access to related information for CSSS updates. This process further strengthens CSSS operability. (4) Government response; when GSA receive comments and suggestions from contractors, they should act quickly to respond, alter their regulatory strategy, and report to SMA to amend CSSS and CSS.

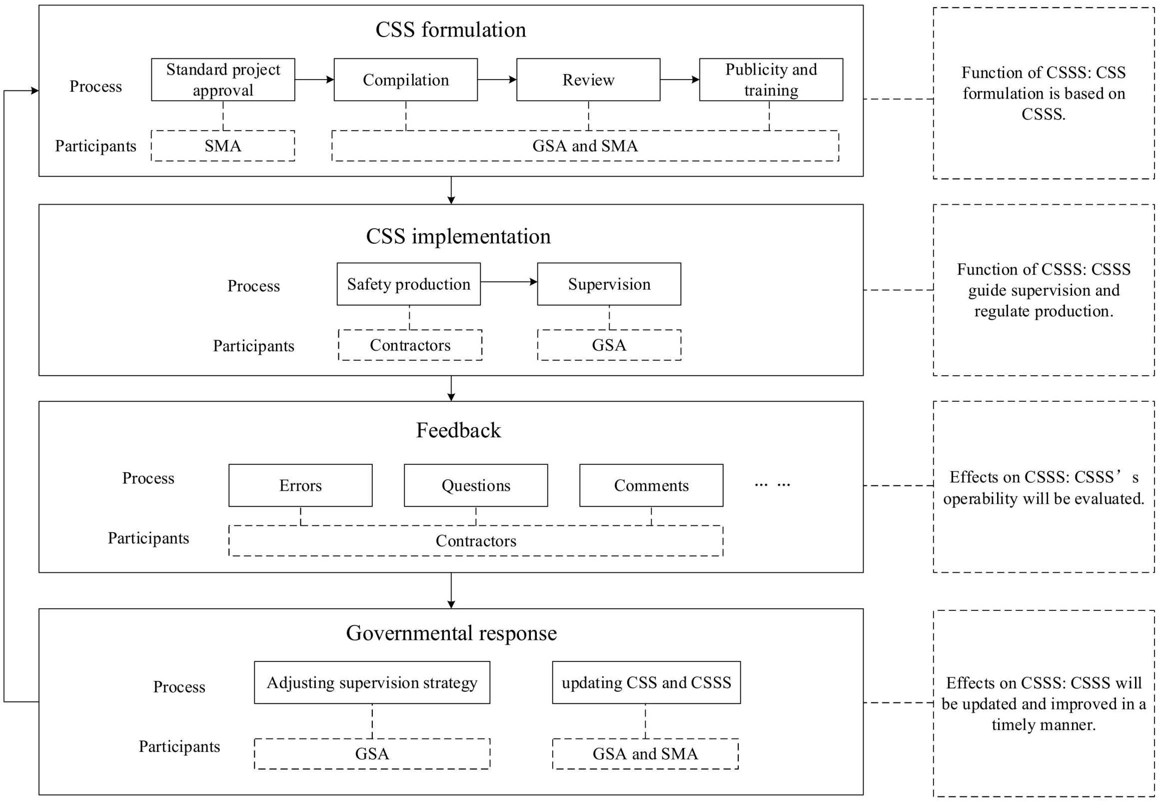

Figure 3. The implementation flow of CSSS Feedback Platform.

3.3. *Evolutionary Game Theory*

As described in Section 2, EG theory concentrates on strategy adjustments [15]. As stakeholders, SMA, GSA, and contractors dynamically adjust strategies to maximize their benefits. Therefore, EG theory is adopted to analyze the behavior between stakeholders.

3.3.1. Evolutionary Game Relationship Description and Strategy Choices

As described in Section 2, we can analyze the game equilibrium state based on replicator dynamic equations [34,39]. The replicator dynamics equation uses a form of dynamic differential equation to describe the probability of a strategy in a group [35]. The game equilibrium state is reached when the increased proportion of the replication dynamics is zero [35]. ESS is the stable equilibrium state that players may eventually reach [39]. If ESS exists, the probability of a particular strategy will remain constant [39]. In the process of reaching ESS, each player's behavior is influenced by other players' current strategies [39]. Therefore, it is important to identify participants and available strategies.

According to the description of CSSS in Section 3.2, the behavior of SMA also has an impact on supervision. Thus, SMA should be considered in the evolutionary game of GSA and contractors. Given this, this paper will establish a multiplayer evolutionary game model that includes SMA, GSA, and contractors. The relationship between stakeholders is shown in Figure 4.

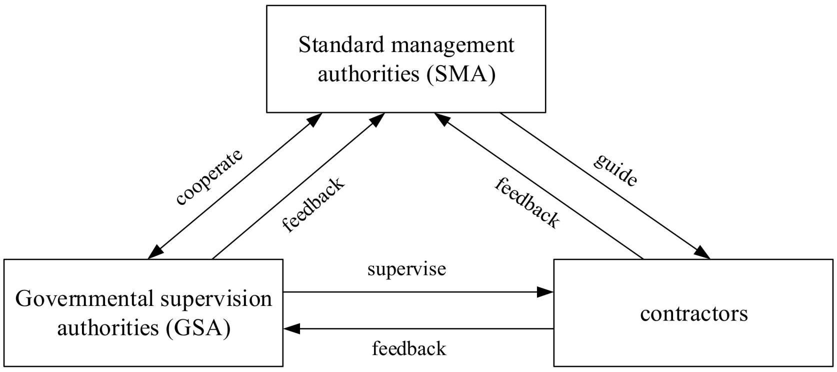

Figure 4. The relationship between stakeholders.

GSA supervise contractors concerning CSS. Considering supervision costs and construction safety requests, GSA's strategy space is {supervision, not supervision}. Contractors are regulated and they should comply with CSSS. Considering safety investments and penalties, contractors' strategy space is {obeying CSS, not obeying CSS}. Considering social benefits obtained by CSSST application and costs of CSSST construction, SMA's strategy space is {making CSSS, not making CSSS}.

3.3.2. Parameters and Payoff Matrix

After discussing with the expert panel of twenty-five construction safety experts mentioned in Section 3.2, We propose the following parameters of three stakeholders.

1. Each player only has two pure strategy choices at time t. Assume that GSA supervises the contractors with a probability x ($0 \leq x \leq 1$). x = 1 implies that GSA supervise the contractors in realtime, then x = 0 implies that GSA choose not to supervise contractors' security operations.
   (1) B_g denotes the expected loss of social benefits as a result of not obeying CSS, including public economic loss and distrust of the society towards the government.
   (2) C_g denotes GSA's supervision costs.
   (3) F denotes the probability of construction accidents.
   (4) N denotes GSA's penalties as a result of negative supervision when accidents occur.
   (5) S_g denotes supervision costs saved due to GSA's CSSST application, including the reduction in personnel and material costs.
2. Assume that the contractors obey CSS with a probability y ($0 \leq y \leq 1$). Therefore, the probability of contractors not obeying CSS is $(1 - y)$.
   (1) π denotes normal revenue from regular safety production.
   (2) C_e represents contractors' safety investments.
   (3) L denotes the expected loss of contractors in case of an accident.
   (4) S_e denotes investments saved due to contractors' CSSS application.
   (5) MP_1 and MP denote contractors' penalties as a result of not obeying CSS when accidents occur. Considering the possibility of supervision errors, P is supervision accuracy without CSSST application, and P_1 is supervision accuracy with CSSST application ($0 < p < p_1 < 1$). M represents contractor's penalties as a result of not obeying CSS. MP_1 and MP will be received by GSA.
3. Assume that SMA make CSSST with a probability z ($0 \leq z \leq 1$). Therefore, the probability of SMA not making CSSST is $(1 - z)$.
   (1) C_s represents making CSSST costs, including research and participant coordination costs.
   (2) U_s represents social benefits obtained by CSSST application, which refers to the enhancement of safety performance in infrastructure projects, the reduction in

supervision costs of the whole industry, and the improvement of supervision efficiency brought by the recognition and wide use of CSSST.

The variables are listed in Table 1 and the payment matrix between GSA, contractors, and SMA is exemplified in Table 2.

Table 1. Meanings of the variables in the multiplayer evolutionary game.

Variables	Meaning of the Variables	Notes
x	Probability of governmental supervision	$0 \leq x \leq 1$
y	Probability of contractors obeying CSS	$0 \leq y \leq 1$
z	Probability of SMA making CSSST	$0 \leq z \leq 1$
U_s	Social benefits of CSSST application	$U_s > 0$
C_s	Costs of CSSST construction	$C_s > 0$
B_g	The expected loss of social benefits as a result of not obeying CSS	$B_g > 0$
C_g	Costs of safety supervision	$C_g > 0$
F	Probability of construction safety accidents	$F > 0$
N	GSA's penalties when accidents occur	$N > 0$
S_g	Supervision costs saved due to GSA's CSSST application	$S_g > 0$
M	Contractors' penalties as a result of not obeying CSS	$M > 0$
P_1	Supervision accuracy with CSSST application	$0 < P_1 < 1$
P	Supervision accuracy without CSSST application	$0 < P < 1$
π	Contractors' normal revenue from regular production	$\pi > 0$
C_e	Contractors' safety investments	$C_e > 0$
L	Contractors' expected loss in case of an accident	$L > 0$
S_e	Investments saved due to contractors' CSSS application	$S_e > 0$

Table 2. Payoff matrix between GSA, contractors, and SMA.

Government	Contractor	
	Obey CSS (y)	**Not Obey CSS (1 − y)**
GSA supervises and SMA makes CSSS, (x, z)	$S_g - C_g$ $\pi - C_e + S_e$ $U_s - C_s$	$S_g + MP_1 - C_g - B_g$ $\pi - FL - MP_1$ $-C_s$
GSA supervises and SMA does not make CSSS, (x, 1 − z)	$-C_g$ $\pi - C_e$ 0	$MP - C_g - B_g$ $\pi - FL - MP$ 0
GSA does not supervise and SMA makes CSSS, (1 − x, z)	0 $\pi - C_e + S_e$ $U_s - C_s$	$-B_g - FN$ $\pi - FL$ $-C_s$
GSA does not supervise and SMA does not make CSSS, (1 − x, 1 − z)	0 $\pi - C_e$ 0	$-B_g - FN$ $\pi - FL$ 0

3.4. System Dynamics Simulation and Validation

As we mentioned in Section 2, multiplayer evolutionary game analysis cannot show the path to the equilibrium state [52], while SD can intuitively reflect strategy changes and help us to observe the game state from a global perspective [50]. Hence, this research adopts SD simulation to verify the EG process and analyze the application effect.

To validate the effectiveness of CSSST, we enter the practical data of safety supervision in China into the SD model. According to the China Statistical Yearbook on Construction [58], the average contractors' income (π) is 6.3% of the overall expense of projects. According to the Shanghai safety input regulation, contractors' safety investments (C_e) are 3% of the overall project expense. Contractors' safety investments account for 0.727% of GDP, and the loss caused by accidents (L) is 2.5% of GDP. According to the Administrative Regulations on the Work Safety of Construction Projects [59], contractors' penalties (M) account for 20–50% of the misappropriated safety investment. The misappropriated safety investment is equal to the safety cost that should be invested minus the actual safety investment. Assuming that the actual safety investment is 2.5% of the overall project expense, we obtain the range of contractors' penalties (M). The ratio of other parameters to the total cost of the construction project was determined after expert seminars. The original estimates of variables are as in Table 3 after pretreatment.

Table 3. Original Estimates of Variables in the SD model.

Variables	U_s	C_s	B_g	C_g	F	N	S_g	M	P_1	P	π	C_e	L	S_e
Initial values	2	1	1	0.6	0.2	0.7	0.2	1	0.98	0.95	20	10	50	2

3.5. Case Studies

We investigated six cases in different regions of China to evaluate the effectiveness of CSSS. Case projects were selected through connection with member companies of the China Construction Safety Industry Association. CSSS has been only carried out on a pilot basis in relatively developed areas of China, such as Beijing and Shanghai. The research team selected signature projects of relatively large contractors, because these projects have basic information systems and the highest potential for the implementation of innovative security methods [60]. Previous research suggests at least four to ten cases when examining complicated correlations [61]. The case study information comes from the Research Report of the Ministry of Housing and Urban-Rural Development on the Safety Standard System of Construction. The summary of the case study information is provided in Table 4.

Table 4. Case Study Information.

No.	Location	Project Type	Scope (RMB)	Contractors	Average Annual Operating Revenue of Contractors from 2017–2020 (RMB)
1	Shanghai	Civil building	505 million	Shanghai Construction Group	23.13 billion
2	Shanghai	Hospital	898 million	China Construction eighth engineering division corp., LTD	26.63 billion
3	Shandong	School	1.715 billion	China Construction eighth engineering division corp., LTD	26.63 billion
4	Beijing	Subway	2.785 billion	China Construction eighth engineering division corp., LTD	26.63 billion
5	Hubei	Airport	1.094 billion	China Construction third engineering division corp., LTD	27 billion
6	Beijing	Subway	977 million	China Construction seventh engineering division corp., LTD	20.63 billion

In particular, all cases included on-site inspections, interviews with the project manager, and the collection of supporting documentation. We also conducted face-to-face interviews with governmental safety supervisors in Beijing, Shanghai, Shandong, and Hubei.

Our interview questionnaire was mainly separated into two components. One was the situation of CSS usage before CSSS application. The purpose of designing this component was to verify the necessity of CSSS. We specifically included the following four questions: (1) Before the application of CSSS, were there any unclear expressions in the provisions of individual construction safety standards? (2) Before the application of CSSS, were there contradictory provisions of individual construction safety standards and codes? (3) Before the application of CSSS, were there a lack of individual key standards? (4) Before the application of CSSS, were individual standards falling behind the industry and technology development? The purpose of this part was only to reflect the problems existing in the CSS application before the CSSS application, these four questions were structured to solicit a yes or no response. The other component was to directly verify the effectiveness of CSSS, and the interview questions for the project manager and governmental safety supervisors were slightly different. For the project manager, it mainly included the following three questions: (1) If the government no longer carries out strong supervision, will the project still be produced according to the standards? (2) Has the efficiency of project safety management been improved after the application of CSSS and with the government's preference for safety supervision? What are the specific aspects? (3) After CSSS application, and with the government's preference for safety supervision, is the motivation for project safety management improved? What are the specific aspects? For the governmental safety supervisors, it mainly included the following two questions: (1) After the application of CSSS, has the efficiency of government safety supervision been improved? What are the specific aspects? (2) Has the enthusiasm for government safety supervision been improved after the application of CSSS? What are the specific aspects? The questionnaires are shown in Appendices A and B.

The questionnaires needed to guarantee internal and external effectiveness [62]. For this reason, the research team did not clarify the definition of safety supervision efficiency in the interview, but explained it with questions like "Do you think your work efficiency and enthusiasm have been improved after CSSS application? In what areas?". Furthermore, we researched different types of projects from four different regions in China to ensure external effectiveness.

4. Results

4.1. Results of The Multiplayer EG and SD Simulation

4.1.1. Replicator Dynamics

As mentioned in Section 2, replicator dynamics was used to describe the probability of a strategy in a system [35]. In the supervision procedure, we can adapt the replication dynamics to demonstrate the strategy adjustment procedure of players. Hence, the replicator dynamic equations of GSA, F(x); Contractors, F(x), and GSA, F(z), are calculated as Equations (1)–(3). The details are presented in Appendix C.

$$F(x) = \frac{dx}{dt} = x \times (1-x) \times [(MP - MP_1) \times y \times z + (MP_1 - MP + S_g) \times z - (MP + FN) \times y + (MP + FN - C_g)] \quad (1)$$

$$F(y) = \frac{dy}{dt} = y \times (1-y) \times [(MP_1 - MP) \times x \times z + S_e \times z + MP \times x + (FL - C_e)] \quad (2)$$

$$F(z) = \frac{dz}{dt} = z \times (1-z) \times (U_s \times y - C_s) \quad (3)$$

4.1.2. SD Flow Chart

According to Sections 3.3, 3.4 and 4.1, we developed a multiplayer evolutionary game SD model by using Vensim PLE (Personal Learning Edition). Vensim is simulation software for visualizing and analyzing dynamic systems, which allows for model veracity checking. The SD flow chart is shown in Figure 5.

The model contains horizontal variables, rate variables, auxiliary variables, and external variables. The relationship between these variables is premised on Equations (1)–(3). Specifically, horizontal variables involve the probability of supervision x, the probability of obeying CSS y, and the probability of making CSSST z, which characterize the accumulation of the system. Rate variables involve the adjustment rate of supervision F(x), the change rate of obeying CSS F(y), and the change rate of making CSSST F(z), which characterize the decision-making procedure. Auxiliary variables refer to transition variables in the calculation. External variables are in line with the original estimates in Table 3. We used different colored lines to demonstrate the GSA supervision submodule, the contractors obeying CSS submodule, and the SMA making CSSST submodule. Detailed SD model equations can be found in Appendix D.

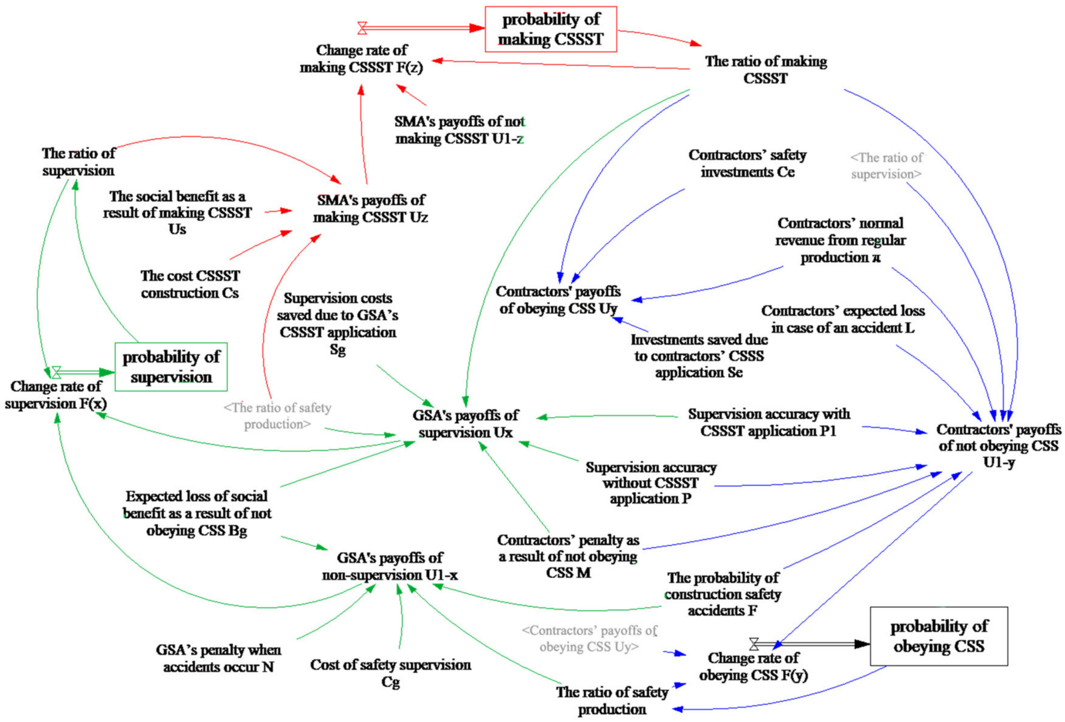

Figure 5. SD flow chart.

4.1.3. Result Analysis of SD Simulation

(1) Impact Analysis of CSSS Implementation

To validate the effectiveness of CSSS, we first compared results under the strategy of making CSSS and not making CSSS. Without loss of generality, let GSA's initial strategy $x_0 = y_0 = 0.5$ and $z_0 = 0$. This represents the case where CSSS is not implemented, which is marked as "CSSS not implemented". When CSSS is implemented, let $x_0 = y_0 = 0.5$ and $z_0 = 0.1$. This case is marked as "CSSS implemented".

The simulation result of GSA is shown in Figure 6. Dmnl is the unit of variables x, y, and z, indicating that their unit is 1. The result illustrates that GSA's strategy selections fluctuate periodically when CSSS is not in use, however, after CSSS is implemented, the fluctuation of GSA's strategy selection could be effectively suppressed.

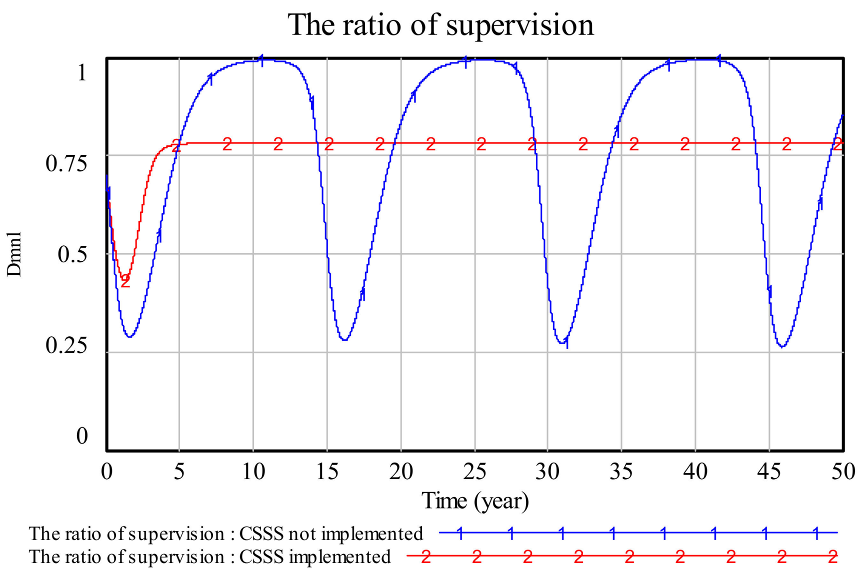

Figure 6. CSSS implementation impact on GSA.

The simulation result of contractors is shown in Figure 7. Dmnl is the unit of variables x, y, and z, indicating that their unit is 1. The result illustrates that the strategic choices of contractors also fluctuate when CSSS is not in use. After the implementation of CSSS, the fluctuation of contractors' strategy selection could be effectively suppressed, thereby stabilizing the game.

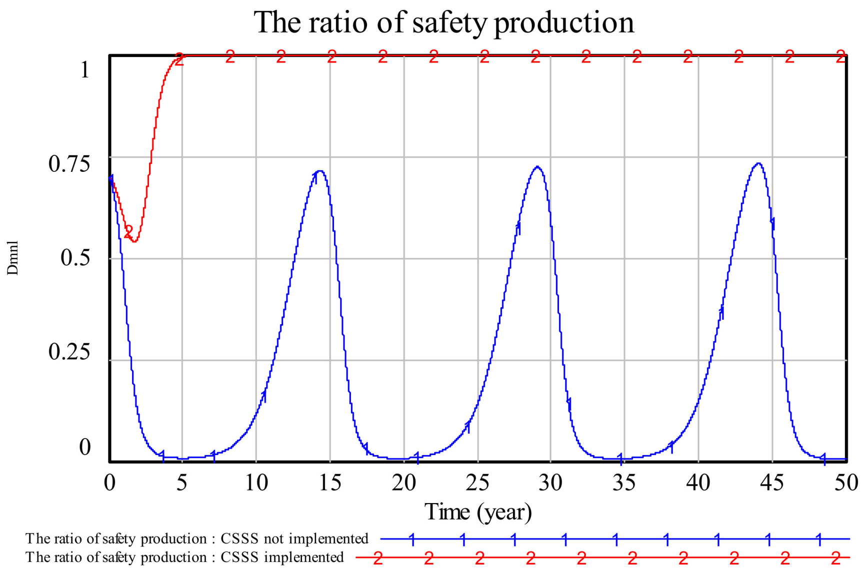

Figure 7. CSSS implementation impact on contractors.

(2) ESS Analysis

ESS is the equilibrium state [39]. If ESS exists, the probability of stakeholders' strategy will eventually remain constant [39]. To analyze whether the evolutionary game system has an ESS, we have the stakeholders start with varied initial strategies. The system has an ESS if the stakeholders' strategy choices eventually evolve to the same steady state. Given this, we set four different groups of initial strategies:

Group 1. current 5: $(x_0, y_0, z_0) = (0.7, 0.7, 0)$, current 6: $(x_0, y_0, z_0) = (0.8, 0.8, 0)$
Group 2. current 7: $(x_0, y_0, z_0) = (0.7, 0.7, 0.1)$, current 8: $(x_0, y_0, z_0) = (0.8, 0.8, 0.1)$

The initial value $z_0 = 0$ in Group 1 represents the case where CSSS is not implemented. The initial value $z_0 = 0.1$ in Group 2 represents the case where CSSS is implemented.

The result is demonstrated in Figures 8 and 9. Dmnl is the unit of variables x, y, and z, indicating that their unit is 1. According to the result, GSA do not have an ESS when CSSS is not implemented. However, after the CSSS application, the probability of GSA choosing a certain strategy eventually remains stable, which demonstrates that GSA have an ESS. Similarly, contractors do not have an ESS before CSSS is implemented. However, the strategy of contractors eventually remains stable after CSSS implementation, which demonstrates that contractors have an ESS.

More importantly, we find that after CSSS implementation, the stable value of the supervision probability $x < 1$ and the stable value of contractors' strategy $y = 1$. This indicates that even if GSA do not supervise every moment, contractors will always comply with CSS. In other words, CSSS implementation is beneficial for contractors to carry out safety production consciously, which will reduce the input of GSA's safety supervision.

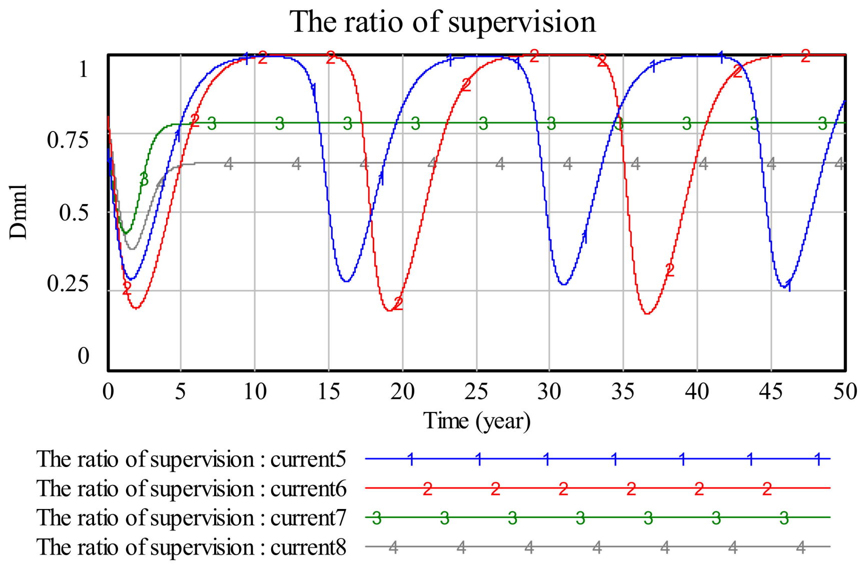

Figure 8. CSSS implementation impact on GSA's ESS.

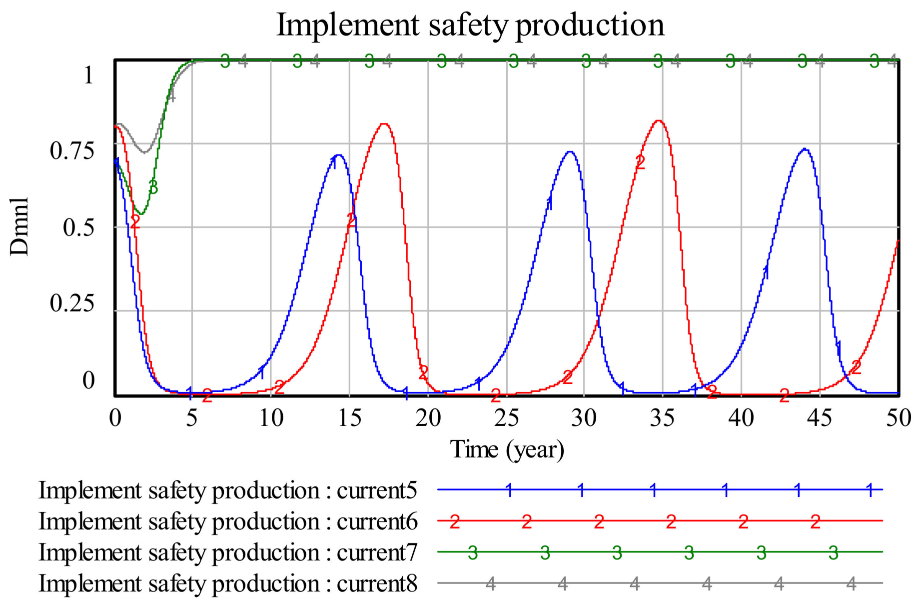

Figure 9. CSSS implementation impact on contractors' ESS.

(3) Impact of U_s on The Equilibrium State

U_s indicates the social benefits of CSSST application on safety supervision. It refers to the enhancement of safety performance in infrastructure projects, the reduction in supervision costs of the whole industry, and the improvement of supervision efficiency brought by the recognition and wide use of CSSST. The increase in U_s illustrates the importance of CSSS implementation and the social expectation of CSSS, which can be demonstrated by the widespread use of CSSS.

To validate the effect of increasing U_s on the equilibrium state, we set different initial strategies:

current 9: $(x_0, y_0, z_0) = (0.5, 0.5, 0.1), U_s = 2$
current 10: $(x_0, y_0, z_0) = (0.5, 0.5, 0.1), U_s = 2.2$

The result is demonstrated in Figures 10 and 11. Dmnl is the unit of variables x, y, and z, indicating that their unit is 1. According to the result, when U_s grows, GSA's strategy selection and contractor strategy selection probability quickly reaches a stable optimal state. It can be demonstrated that improving social benefits of CSSS implementation is an efficient measure to optimize construction safety supervision. Therefore, the government should comply with the following request.

(1) When we develop CSSS, the content of CSSS should meet the actual needs of the market.
(2) When we promote CSSS, the measures should be as diverse as possible.

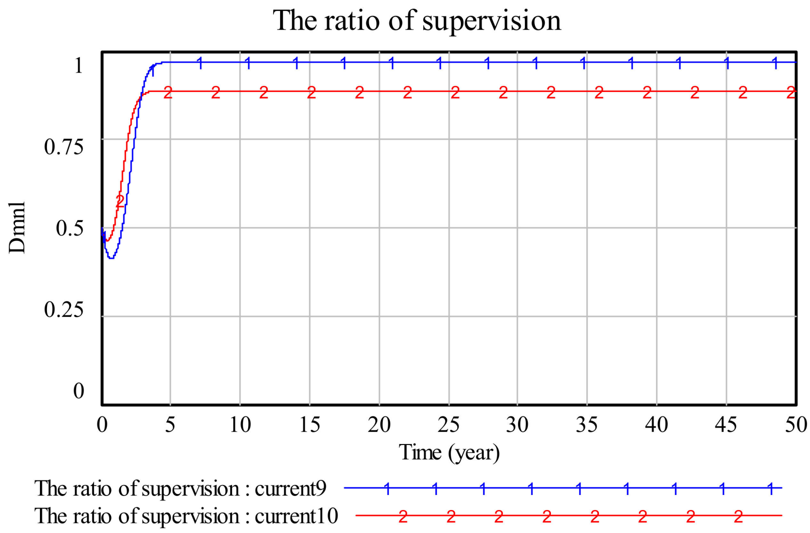

Figure 10. Impact of Us on the equilibrium state of GSA.

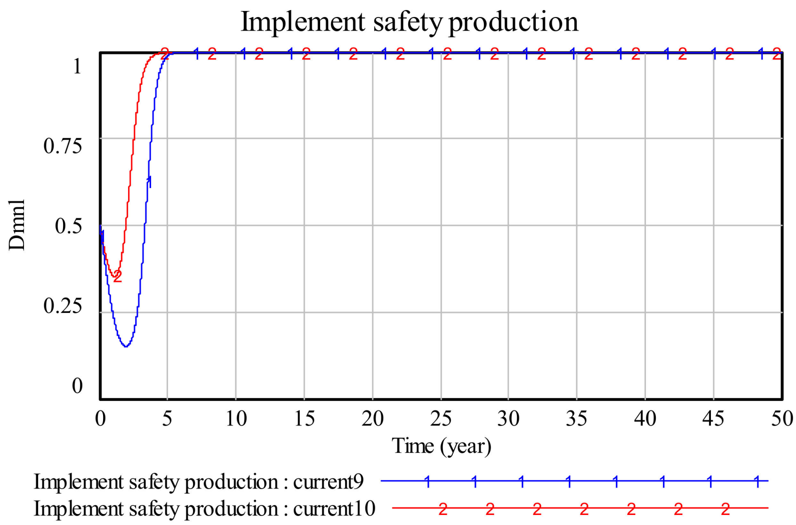

Figure 11. Impact of Us on the equilibrium state of contractors.

4.2. Results of Case Studies

As we mentioned in Section 3.5, our interview questionnaire evaluated the effectiveness of CSSS in the real world. It was mainly separated into two components. One was the situation of CSS usage before CSSS application. The purpose of designing this part was to verify the necessity of the CSSS. The other was to directly verify the effectiveness of CSSS, and the interview questions for the project manager and governmental safety supervisors were slightly different. The following three subsections analyze the results of the first and second parts in detail.

4.2.1. The Situation of CSS Usage before CSSS Application

This part was to verify the necessity proposed by CSSS. Project managers of six different projects and government supervisors of four different regions believe that before CSSS application, individual CSSs had unclear expressions and contradictory requirements, and there was a lack of individual key CSSs. In addition, individual CSSs fell behind the industry and technology development. For instance, "Wire Rope Clamp" specifies that the diameter of wire rope is less than or equal to 9 mm, and rope card may not include less than 3 groups, while "Safe Use and Maintenance of Wire Rope", "Construction Machinery Use Safety Technical Regulations", "Construction Tower Crane Installation, Use, Dismantling Safety Technical Regulations" require the diameter of wire rope less than or equal to 18 mm, and rope card may not include less than 3 groups. This is consistent with the current status of CSS application mentioned in the introduction. Given this, CSSS can unify government supervision and contractors' safety production standards, improve the integration and operability of CSS, and maximize the role of CSS in the process of safety supervision.

4.2.2. The Impact of CSSS Application on Contractors

This part was to identify project security management changes after CSSS application. If the efficiency and enthusiasm of safety management in contractors had improved, the effectiveness of CSSS for contractors was verified.

For the first question, after CSSS implementation, assuming that the government will no longer supervise, two project managers said that safety is crucial to the sustainability of the project and they will obey CSS as usual. However, the remaining four project managers did not give a positive answer about obeying CSS. One of them said, "Nowadays, the competition in the Chinese construction market is very fierce. Especially under the influence of COVID-19, the productivity of contractors has been affected, and contractors will pay more attention to the short-term income to obtain survival." This shows that CSSS application will not significantly improve the status quo of contractors obeying CSS without the involvement of GSA.

GSA involved in CSSS implementation is the actual situation faced by the six selected projects. All six project managers reported improvement in the efficiency and motivation of project safety management. Specifically, CSSS integrates a large number of standards and presents them in the form of CSSST, which alleviates the issues of contradictory individual provisions. The CSSS feedback platform deepens construction workers' understanding of CSS and allows timely communication in the platform on problems encountered at construction sites to obtain safer construction solutions, effectively reducing construction workers' unsafe behavior, and greatly reducing the workload of project managers. In this way, managers can carry out fewer safety corrections, increase the efficiency of safety management, spend more time and energy on CSSS application improvement, and their work motivation is promoted.

It has been noted that a decrease in unsafe behavior, i.e., a decrease in the number of project safety corrections, is associated with an improvement in project safety performance [63–67]. After observing weekly site meetings, we found that all six projects did enhance their safety performance at a different level. Project 1 reduced the number of weekly safety corrections from 10 to 5. Project 2 reduced the number of weekly safety corrections from 10 to 8. Project 3 reduced the number of weekly safety corrections from 12 to 9. Project 4 reduced the number of weekly safety corrections from 8 to 5. Project 5 reduced the number of weekly safety corrections from 10 to 7. Project 6 reduced the number of weekly safety corrections from 10 to 5 after three months of CSSS implementation.

In summary, CSSS application has improved the efficiency and enthusiasm of safety management in contractors under government-imposed safety supervision.

4.2.3. The Impact of CSSS Application on GSA

This part was to identify changes in government safety supervision after CSSS application. If the efficiency and enthusiasm of governmental safety supervision had improved, the effectiveness of CSSS for GSA was verified.

After CSSS application, four governmental supervisors from different regions of China reported a reduction in the number of safety corrections. However, the reduction in supervision costs was not significant because CSSS was piloted in the region, and it was only applied to major projects, due to the different completeness of information systems and other infrastructure of each contractor.

Nevertheless, four governmental supervisors all expressed their optimism about the future of CSSS. They suggested that the content of CSSS should meet the actual needs of the market, and the standard management should widely adopt suggestions from regulators and contractors to achieve a better CSSS application. In addition, when promoting CSSS, the measures should be diverse, which is still a difficult task.

5. Discussion

In line with previous studies, Figures 6 and 7 illustrate that the stakeholders' strategy choices show period fluctuations [68]. This is reflected in the fact that when GSA conduct positive supervision, contractors will choose to obey CSS because of heavy penalties. Therefore, the construction safety atmosphere improves and GSA's supervision strategy gradually slackens. However, when contractors perceive that GSA tend to conduct negative supervision, they will gradually evade the responsibility of safety control. Thus, the probability of accidents increases and GSA strengthen supervision. Given this, there is a time lag in maintaining construction safety through supervision because the government cannot adjust its supervision strategy in time to respond to changes in contractor decisions. Contractors are usually forced to obey CSS due to external supervision pressure, which reduces the enthusiasm for safety production.

Different from previous studies [69], this paper has two new findings as follows.

(1) Through CSSS implementation, the strategy choice fluctuation of GSA and contractors is suppressed and a more desirable stable equilibrium is reached. GSA tend to supervise and contractors tend to obey CSS. More importantly, we find that after CSSS implementation, the probability of supervision (x) has a stable value of less than 1, while the probability of obeying CSS (y) eventually remains stable at 1. This indicates that even if GSA do not supervise every moment, contractors will comply with CSS. Therefore, CSSS implementation is beneficial for contractors to obey CSS consciously, which will reduce the cost of GSA's safety supervision.

(2) Solely improving the social benefit of CSSS implementation is an efficient measure to optimize construction safety supervision. Therefore, the government should meet the request: (1) When we develop CSSS, the content of CSSS should meet the actual needs of the market. (2) When we promote CSSS, the ways should be as diverse as possible.

According to the research results, we put forward the following recommendations.

(1) SMA should appropriately decentralize their management responsibilities and allow GSA to participate in CSS creation, revision, and planning. In addition, in the process of CSSS formulation, SMA should adopt professional opinions of GSA and contractors on issues such as CSS classification and catalog determination, so that CSSS can better meet market requirements.

(2) GSA should strengthen its cooperation and communication with SMA to help establish CSSS, reach an agreement with contractors on CSSS application, reduce unnecessary coordination in supervision, save supervision costs, and improve the social benefits of CSSS. Meanwhile, it is helpful to improve GSA's supervision accuracy.

(3) Contractors should actively participate in the development and improvement of CSSS. They should also update CSS in conjunction with new processes and materials that have been applied maturely on-site to occupy a leading position in the industry. In addition, they should actively put them into production following the requirements of the local GSA.

6. Conclusions

CSS and safety supervision are of vital importance to labor safety and the sustainable development of the construction industry. Few studies have combined CSS and safety supervision. In this study, CSSS was constructed and provided for supervision parties to establish the link between CSS and safety supervision. In terms of research methodology, this paper described and analyzed the impact of CSSS implementation on the strategic choices of safety supervision parties by using EG theory and SD simulation. The findings are as follows.

(1) CSSS integrates standards effectively, so CSSS implementation accommodates SMA, GSA, and contractors into an evolutionary system that facilitates overall system analysis.
(2) CSSS formulation and implementation can suppress the fluctuation of GSA and contractors' strategy choices. The probability of GSA's supervision and contractors' safety production can reach an ideal stable state, which verifies the effectiveness of CSSS in safety supervision.
(3) After CSSS implementation, GSA's supervision efficiency increases. In addition, CSSS application has improved the efficiency and enthusiasm of safety management in contractors under government-imposed safety supervision.
(4) Improving the social benefits of CSSS application (U_s) will enable GSA and contractors' strategy selections to quickly reach a steady state. Given this, improving the social benefits of CSSS application is an efficient measure to optimize the effectiveness of construction safety supervision.

This paper has theoretical and practical implications. From the theoretical aspects, (1) the positive effect of CSSS on construction safety supervision was verified theoretically. (2) Evolutionary game theory and SD simulation were combined to quantitatively analyze the safety supervision behavior under the participation of SMA, which also provided an effective method to study system behavior. From the practical aspects, (1) the CSSS proposed in this paper unified standards, improved the operability of CSS, and maximized the role of standards in safety supervision. (2) We established and implemented CSSS in the construction industry in China, and other countries could establish their own CSSS based on the principles and methods proposed in this paper. In addition, CSSS can also be extended to other industries to help sustainable development.

However, there are some limitations to this paper. SMA, GSA, and contractors were regarded as stakeholders. The influence of other stakeholders such as owners was not considered. In addition, because CSSS is an innovative method that has not been widely adopted, we could not explain the deeper impact of CSSS on government regulatory agencies and contractors. This is desirable for future work.

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Appendix A

Interview Questions for Project Manager
1. The situation of CSS usage before the CSSS application. (1) Before the application of CSSS, were there any unclear expressions in the provisions of individual construction safety standards? ☐Yes ☐No (If yes, please give examples) (2) Before the application of CSSS, were there contradictory provisions of individual construction safety standards and codes? ☐Yes ☐No (If yes, please give examples) (3) Before the application of CSSS, was there a lack of individual key standards? ☐Yes ☐No (If yes, please provide examples) (4) Before the application of CSSS, were individual standards falling behind the industry and technology development? ☐Yes ☐No (If yes, please give examples) 2. Project security management changes after CSSS application. (1) If the government no longer carries out strong supervision, will the project still be produced according to the standards? (2) Has the efficiency of project safety management been improved after the application of CSSS and with the government's preference for safety supervision? What are the specific aspects? (3) After CSSS application, and with the government's preference for safety supervision, is the motivation of project safety management improved? What are the specific aspects?

Appendix B

Interview Questions for Government Supervision Authorities
1. The situation of CSS usage before CSSS application. (1) Before the application of CSSS, were there unclear expressions in the provisions of individual construction safety standards? ☐Yes ☐No (If yes, please give examples) (2) Before the application of CSSS, were there contradictory provisions of individual construction safety standards and codes? ☐Yes ☐No (If yes, please give examples) (3) Before the application of CSSS, was there a lack of individual key standards? ☐Yes ☐No (If yes, please provide examples) (4) Before the application of CSSS, were individual standards falling behind the industry and technology development? ☐ Yes ☐ No (If yes, please give examples) 2. Changes in government safety supervision after CSSS application. (1) After the application of CSSS, has the efficiency of government safety supervision been improved? What are the specific aspects? (2) Has the enthusiasm for government safety supervision been improved after the application of CSSS? What are the specific aspects?

Appendix C

In Section 4.1, the details to obtain the replicated dynamic equations are as follows:

(1) Replicated dynamic equation of GSA

It is supposed that the profit when the government supervises is U_x, and the payoff when supervision is not conducted is U_{1-x}, and the average expected fitness is denoted by $\overline{U_x}$. The representative equations are as follows:

$$U_x = (S_g - C_g)yz + (S_g + MP_1 - C_g - B_g)(1 - y)z + (-C_g)(1 - z)y + (MP - C_g - B_g)(1 - y)(1 - z)$$

$$U_{1-x} = (-B_g - FN)(1 - y)z + (-B_g - FN)(1 - y)(1 - z)$$

$$\overline{U_x} = xU_x + (1 - x)U_{1-x}$$

According to EG theory, the replicated dynamic equation of the supervision sector is as follows:

$$F(x) = \frac{dx}{dt} = x\left(U_x - \overline{U_x}\right) = x(1 - x)(U_x - U_{1-x})$$

$$= x(1 - x)[(MP - MP_1)yz + (MP_1 - MP + S_g)z - (MP + FN)y + (MP + FN - C_g)]$$

(2) Replicated dynamic equation of contractors

Similarly, the expected payoffs when contractors choose to obey CSS and not obey CSS are symbolized as U_y and U_{1-y} respectively, and the average expected fitness is denoted by $\overline{U_y}$. The representative equations are as follows:

$$U_y = (\pi - C_e + S_e)xz + (\pi - C_e)(1 - z)x + (\pi - C_e + S_e)(1 - x)z + (\pi - C_e)(1 - x)(1 - z)$$

$$U_{1-y} = (\pi - FL - MP_1)xz + (\pi - FL - MP)(1 - z)x + (\pi - FL)(1 - x)z + (\pi - FL)(1 - x)(1 - z)$$

$$\overline{U_y} = yU_y + (1 - y)U_{1-y}$$

Further, the dynamic replication equation of contractors is shown as follows:

$$F(y) = \frac{dy}{dt} = y(1 - y)[(MP_1 - MP)xz + S_e z + MPx + (FL - C_e)]$$

(3) Replicated dynamic equation of SMA

The expected payoffs when SMA select to establish CSSST and not to establish CSSST are symbolized as U_z and U_{1-z}, and the total fitness is denoted by $\overline{U_z}$. The representative equations are as follows:

$$U_z = (U_s - C_s)xy + (-C_s)(1 - y)x + (U_s - C_s)(1 - x)y + (-C_s)(1 - x)(1 - y)$$

$$U_{1-z} = 0$$

$$\overline{U_z} = zU_z + (1 - z)U_{1-z}$$

The dynamic replicated equation of SMA is calculated as follows:

$$F(z) = \frac{dz}{dt} = z(1 - z)(U_s y - C_s)$$

Appendix D

The model equations of Figure 5.

Main equations of GSA's strategy:

(1) "GSA's payoffs of supervision (U_x)" = "The ratio of safety production (y)" * "The ratio of making CSSST (z)" * ("Contractors' penalty as a result of not obeying CSS (M)" * "Supervision accuracy without CSSST application (P)" − "Contractors' penalty as a result of not obeying CSS (M)" * "Supervision accuracy with CSSST application (P1)") + ("Expected loss of social benefit as a result of not obeying CSS (B_g)" − "Contractors' penalty as a result of not obeying CSS (M)" * "Supervision accuracy without CSSST application (P)") * "The ratio of safety production (y)" + ("Supervision costs saved due to GSA's CSSST application (S_g)" + "Contractors' penalty as a result

of not obeying CSS (M)” * “Supervision accuracy with CSSST application (P_1)” − “Contractors’ penalty as a result of not obeying CSS (M)” * “Supervision accuracy without CSSST application (P)”) * “The ratio of making CSSST (z)” + “Contractors’ penalty as a result of not obeying CSS (M)” * “Supervision accuracy without CSSST application (P)” − “Expected loss of social benefit as a result of not obeying CSS (B_g)”

(2) “GSA’s payoffs of non-supervision (U_{1-x})” = (“Expected loss of social benefit as a result of not obeying CSS (B_g)” + “The probability of construction safety accidents (F)” * “GSA’s penalty when accidents occur (N)”) * “The ratio of safety production (y)” + “Costs of safety supervision (C_g)” − “The probability of construction safety accidents (F)” * “GSA’s penalty when accidents occur (N)”

(3) “Change rate of supervision (F(x))” = “The ratio of supervision (x)” * (1 − “The ratio of supervision (x)”) * (“GSA’s payoffs of supervision U_x” − “GSA’s payoffs of non-supervision U_{1-x}”)

Main equations of contractors’ strategy:

(1) “Contractors’ payoffs of obeying CSS (U_y)” = “Investments saved due to contractors’ CSSS application (S_e)” * “The ratio of making CSSST (z)” + “Contractors’ normal revenue from regular production (π)” − “Contractors’ safety investments (C_e)”

(2) “Contractors’ payoffs of not obeying CSS (U_{1-y})” = (“Contractors’ penalty as a result of not obeying CSS (M)” * “Supervision accuracy without CSSST application (P)” − “Contractors’ penalty as a result of not obeying CSS (M)” * “Supervision accuracy with CSSST application (P_1)”) * “The ratio of making CSSST (z)” * “The ratio of supervision-Contractors’ penalty as a result of not obeying CSS (M)” * “Supervision accuracy without CSSST application (P)” * “The ratio of supervision (x)” + “Contractors’ normal revenue from regular production (π)” − “The probability of construction safety accidents (F)” * “Contractors’ expected loss in case of an accident (L)”

(3) “Change rate of obeying CSS (F(y))” = “The ratio of safety production (y)” * (1 − “The ratio of safety production (y)”) * (“Contractors’ payoffs of obeying CSS (U_y)” − “Contractors’ payoffs of not obeying CSS (U_{1-y})”)

Main equations of SMA’s strategy:

(1) “SMA’s payoffs of making CSSST (U_z)” = “−The social benefit as a result of making CSSST (U_s)” * “The ratio of supervision (x)” * “The ratio of safety production (y)” + “The social benefit as a result of making CSSST (U_s)” * “The ratio of supervision (x)” + “The social benefit as a result of making CSSST (U_s)” * “The ratio of safety production (y)” − “The cost CSSST construction (C_s)”

(2) “SMA’s payoffs of not making CSSST (U_{1-z})” = 0

(3) “Change rate of making CSSST (F(z))” = “The ratio of making CSSST (z)” * (1 − “The ratio of making CSSST (z)”) * (“SMA’s payoffs of making CSSST (U_z)” − “SMA’s payoffs of not making CSSST (U_{1-z})”)

Note: “*” stands for multiplying

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