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Promotion Strategy of Smart Construction Site Based on Stakeholder: An Evolutionary Game Analysis

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Abstract: Smart Construction Sites (SCS) are important drivers for the construction of high-quality development. In order to determine the evolution of SCS advancement systems, an evolutionary game model consisting of government, enterprises and projects was constructed. The experimental simulations were performed by using a system dynamics approach. The findings were as follows: (1) There are three stable equilibrium strategies in the evolution of the game system: government, enterprises and projects all adopt positive strategies; government intervention, enterprises' advancement, and projects' non-participation; and government intervention, enterprises and projects adopting negative strategies. (2) Government penalties and balance of interests between enterprises and projects are the main factors affecting the evolution. (3) In the state (1,1,1), the influence of a government regulatory system is more significant in encouraging enterprises to promote SCS and projects to participate in building an SCS platform. (4) Government rewards and penalties, costs and benefits of corporate support for SCS, benefits when projects do not participate in SCS, are the main factors influencing the adoption of proactive strategies by companies and projects, and there are significant differences in the strategic directions and marginal impacts of each factor on stakeholders' choices. These findings provide a reference for further refining stakeholder theory and for promoting the sustainable development of SCS.

Keywords: smart construction site; stakeholder; evolutionary game theory; system dynamics



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1. Introduction

With the rapid development of the construction industry, the number and scale of construction sites continue to expand. Problems such as extensive development methods, imperfect regulatory mechanisms, and a low level of informatization have become increasingly prominent [1,2]. At the same time, the development of information technologies such as the Internet of Things and big data have gradually changed the organizational structure and production methods of various industries. The demand for informatization in the construction industry has become more and more urgent. Smart construction sites (SCS) use information technology to develop intelligent systems and supervision platforms, which can help traditional construction sites solve many problems, which can accomplish safe, efficient, and high-quality construction [3]. Compared with traditional construction sites, smart construction sites have a larger investment scale, more stakeholders, and a more complex organizational structure [4].

In engineering activities, the problems of different goals, conflicting demands and information obstruction among construction participants have become increasingly acute [5]. To enhance information sharing among participants, the concept of SCS was proposed. Government and construction enterprises have certain demands on them. Industry 4.0 brings the trend towards digitalization, automation, and widespread use of information technologies [6]. In the ear of Industry 4.0, the government would like to use SCS to realize information supervision of enterprises and projects, while enterprises hope to improve

their management ability. However, due to the huge investment costs, enterprises need to consider their own profits and actual conditions. Meanwhile, some enterprises and projects are reluctant to fully disclose construction site data to the government, which leads to conflicts between cost input and information sharing between them. The advancement of SCS is the result of a multi-stakeholder game. Despite the availability and popularity of many technologies and typical cases in China [7], SCS is not widely adopted worldwide [8]. Only by clarifying the relationship between various stakeholders in SCS can the development be better promoted. Therefore, it is a topic worthy of discussion to define and analyze the relationship between stakeholders of SCS, resolve their conflicts and contradictions, and establish a continuous promotion mechanism.

As a new management technology and concept, SCS has been mostly studied by scholars in terms of related technology application and system framework construction. This concept originated from Smart City (SC). SC is the intersection of traditional cities and information technology to achieve urban government and to improve living standards through the application of new technologies [9,10]. Citizen participation has an important impact on the sustainable social development and it is based on the public information infrastructure [11]. SC is the key to achieving sustainable social development and can effectively improve the quality of life through SC construction [12]. Based on the development of the smart city concept, the construction industry started to introduce the concept of smart construction. Building Information Modeling (BIM) is beginning to be widely used in construction project management, providing architectural, engineering and construction professionals with the tools to more effectively plan, design and manage construction activities [13]. SCS can also effectively solve the problem of construction environment pollution brought about by traditional construction sites, which can provide workers with a better environment [14]. Internet of Things (IoT), blockchain and Geographic Information System (GIS) are integrated with BIM to achieve a digital application of engineering projects [5,15,16]. Besides this, Virtual Reality (VR) is applied to construction sites to realize project quality and construction safety management by visualizing hazard sources [17,18]. At the same time, the psychological and physiological state of workers is influenced by the surrounding environment, and this influence can be measured by brain waves [19,20]. The future development of smart construction sites can realize a human-centered management model. SCS can improve the efficiency of construction personnel, enhance the comprehensive control ability of sites, reduce sick buildings and increase healthy buildings [21–23], and can promote the overall improvement of the industry supervision level. The development process of SCS needs to reflect the regulatory role of enterprises and the government in the construction market. The government holds a dominant position in promoting policies related to the construction industry [24]. This paper will focus on the strategic choices of enterprises and projects under government intervention.

Stakeholders are the focus of driving SCS development. In the construction, different interests will produce two kinds of relations, such as cooperation and confrontation. If the stakeholders of an engineering project ignore the risks, it will affect the construction process of the project [25]. A strong degree of coordination among stakeholders can effectively facilitate the project process, and differentiation strategies are important in this process [26]. Project performance is an important factor in achieving stakeholder collaboration and is closely related to construction costs [27,28]. SCS development involves a complex network of relationships involving multiple independent stakeholders [29]. Therefore, the coordination of various stakeholders is a prerequisite to guarantee the sustainable development of it. The concept of stakeholders has been widely used in social performance evaluation, and individuals and groups that have an impact on the acquisition of organizational goals can be defined as this [30–32]. Methods such as social network analysis are also used in research to identify stakeholders [33], and, combined with the characteristics of SCS, the stakeholders studied in this paper are those who have invested in the platform construction costs in the process of its promotion and have been affected by the implementation of it. They are the organizations and individuals who have been affected

by the implementation of SCS. This paper aims to build an SCS promotion system with enterprises as the main body, government as the guide, and project parties as participants.

SCS is a complex system project with many stakeholders, and the participation strategies of the government, enterprises and projects play a crucial role in it. The current status of SCS promotion cannot meet the needs of the society, and so it is necessary to improve the efficiency by coordinating the relationship of various stakeholders. Stakeholder management requires coordination of interests based on the characteristics and interests of the parties involved, which needs to be reflected in each phase of the project [34]. In the context of imperfect government mechanisms, uncertain market demand, and uneven innovation costs and benefits [35,36], the effectiveness of the SCS promotion system depends on the strategies of each stakeholder due to differences in participants' interests, asymmetric information, and irrational factors [37,38].

Promoting SCS in the case of multi-subject participation, it is important to identify the strategic choices of stakeholders in various scenarios. The factors influencing the evolutionary state of the system equilibrium include the stable equilibrium state, the preconditions for SCS, the strategy choice of subjects, and external variables. Previous research has failed to give comprehensive explanations and analyses. In this research, we use a dynamic evolutionary game model to portray the relationship between the key stakeholders of SCS and in order to determine the factors affecting system equilibria and strategy selections of stakeholders in various scenarios. External factors are listed on the basis of the system evolution results and sensitivity analysis is performed. The findings are discussed to provide a theoretical basis and suggestions for stakeholders of SCS in order to make strategy decisions.

2. Research Methodology

The theoretical framework in this study consists of three main parts, as shown in Figure 1. The first part is to identify the key stakeholders. Based on the analysis of interest demands and conflict, a Mitchell scoring method is used to clarify that government, enterprises and projects are the key stakeholders of SCS development [39]. Secondly, based on evolutionary game theory, the payoff matrix of the three parties of the game is calculated, the replication dynamic equations are listed and the system equilibrium point analysis is performed. Finally, numerical simulations using system dynamics methods and Vensim Personal Learning Edition (PLE) are used to explore the effect of government intervention on the equilibrium point of the system, and the effect of exogenous variables on the system evolution is explored through sensitivity analysis.

2.1. Model Building

The ecology, which was used to examine ecological phenomena, influenced the creation of evolutionary game theory. The basic analysis process of evolutionary game theory includes three processes: random matching game, dynamic evolution equation and evolutionary stability strategy [40]. According to the research problems and the requirements of evolutionary game theory, the following assumptions are made and the meanings of parameters are given in Table 1.

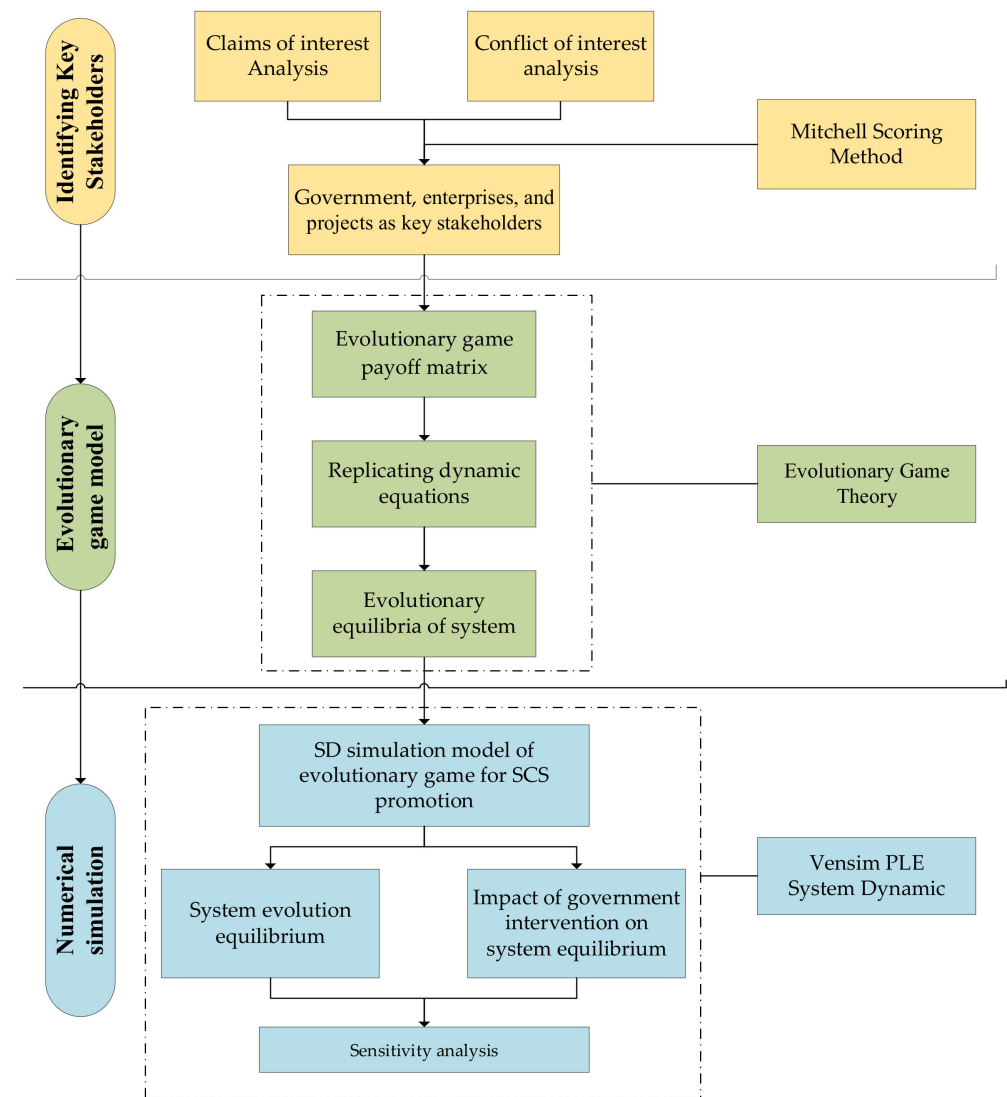


Figure 1. Research Methodology.

Table 1. Glossary of symbols.

Notation	Stakeholders	Explanation
P_1	Government	The fine of enterprises for adopting non-promotion strategy
G_1		The reward of enterprises for adopting promotion strategy
G_2		The reward of projects for adopting promotion strategy
R_1		The revenue of government for adopting intervention strategy
C_1		The cost of SCS intervention
C_2	Enterprises	The loss of construction industry development
C_3		The cost of SCS promotion
C_4		The cost of information barrier paid by enterprises
R_2		The revenue of enterprises adopting a promotion strategy
R_3		The revenue of enterprises adopting a non-promotion strategy
C_5	Projects	The cost of projects for adopting supporting strategy
R_4		The revenue of projects for adopting supported strategy
R_5		The additional revenue when both enterprises and projects choose a positive strategy
R_6		The revenue of projects adopting an unsupported strategy

2.1.1. Assumptions and Parameter

1. The core stakeholders of SCS refer to government, enterprises, and projects.

2. Each participant in the SCS has rational limitations; that is, they cannot accurately calculate its costs and benefits. As a result, each agent attempts many tactics before settling on a certain stabilizing strategy [41,42]. The probability of governments taking a strategy of intervention (A_1) is α ($\alpha \in [0, 1]$), and the opposite strategy (A_2) is $1 - \alpha$. The probability of enterprises taking a strategy of promotion (B_1) is β ($\beta \in [0, 1]$), and the opposite strategy (B_2) is $1 - \beta$. Therefore, the probability of projects taking a strategy of supported (D_1) is γ ($\gamma \in [0, 1]$), and the opposite strategy (D_2) is $1 - \gamma$.
3. When a government adopts strategy A_1 , it may provide services and take preferential measures to enterprises and projects. The cost of intervening in promoting SCS is C_1 . We assume that the reward for enterprises adopting strategy B_1 and the projects adopting strategy D_1 are G_1 and G_2 . When the enterprises adopt strategy B_2 , the government fine on them is P_1 . There are no preferential measures for projects which do not provide SCS. The revenue of strategy A_1 is R_1 . The loss of construction industry development is C_2 if the government adopts strategy A_2 .
4. When enterprises promote SCS, it will take long term benefits, cost, and the development of SCS. The cost and revenue of enterprises adopting strategy B_1 are C_3 and R_2 . They would gain G_1 from the government. However, the revenue of enterprises is R_3 in strategy B_2 . When the projects support SCS and enterprises do not promote SCS, the cost of information barrier paid by enterprises is C_4 .
5. The cost and revenue of projects for adopting strategy D_1 are C_5 and R_4 . They would gain G_2 from the government. When both enterprises and projects choose a positive strategy, the additional revenue that projects can gain is R_5 . Finally, the revenue of projects adopting strategy D_2 is R_6 .

2.1.2. Payoff Matrix and Replication Dynamic Equation

The government, enterprises and projects play different roles and functions in the development of smart construction sites, and there are also different interest demands and conflicts. The three-part evolutionary game model methodically takes the impact of the key stakeholders on the development of SCS into consideration. The model is the first to study the propulsion mechanism of SCS and analyzes the factors influencing the evolution of the system. Based on the above assumptions, the payment matrices for three participants in different situations can be obtained as shown in Tables 2 and 3.

Table 2. Payment matrix under government selective intervention strategy.

Strategic Choices of Enterprises	Project Support the SCS $D_1(\gamma)$		
	Government	Enterprises	Projects
Enterprises promote SCS $B_1(\beta)$	$R_1 - G_1 - G_2 - C_1$	$R_2 + G_1 - C_3;$	$G_2 + R_4 + R_5 - C_5$
Enterprises reject SCS $B_2(1 - \beta)$	$R_1 + P_1 - G_2 - C_1$	$R_3 - P_1 - C_4;$	$G_2 + R_4 - C_5$
	Project nonsupport the SCS $D_1(1 - \gamma)$		
	Government	Enterprises	Projects
Enterprises promote SCS $B_1(\beta)$	$R_1 - G_1 - C_1;$	$R_2 + G_1 - C_3;$	R_6
Enterprises reject SCS $B_2(1 - \beta)$	$R_1 + P_1 - C_1;$	$R_3 - P_1;$	R_6

Table 3. Payment matrix under government selective non-intervention strategy.

Strategic Choices of Enterprises	Project Support the SCS $D_1(\gamma)$		
	Government	Enterprises	Projects
Enterprises promote SCS $B_1(\beta)$	$-C_2$	$R_2 - C_3$	$R_4 + R_5 - C_5$
Enterprises reject SCS $B_2(1 - \beta)$	$-C_2$	$R_3 - C_4$	$R_4 - C_5$
	Project nonsupport the SCS $D_1(1 - \gamma)$		
	Government	Enterprises	Projects
Enterprises promote SCS $B_1(\beta)$	$-C_2$	$R_2 - C_3;$	R_6
Enterprises reject SCS $B_2(1 - \beta)$	$-C_2$	R_3	R_6

The three participants in the SCS system will alter their methods through continual learning, imitation and trial and error, resulting in a dynamic replication process. Replicator dynamics can be described by a dynamic differential equation to represent the change trend of a strategy adopted in the system [43]. The payoff matrices can be used to determine the expected and overall benefit for government, as in Equation (1).

$$\begin{cases} W_{A1} = -\beta(P_1 + G_1) - \gamma G_2 + R_1 + P_1 - C_1 \\ W_{A2} = -C_2 \\ W_A = \alpha W_{A1} + (1 - \alpha)W_{A2} \end{cases} \quad (1)$$

From Equation (1), the replication dynamic differential equation for the strategic alignment of government is Equation (2).

$$F(\alpha) = \frac{\partial \alpha}{\partial t} = \alpha(W_{A1} - W_A) = \alpha(1 - \alpha)(W_{A1} - W_{A2}) = \alpha(1 - \alpha)[- \beta(P_1 + G_1) - \gamma G_2 + R_1 + P_1 - C_1 + C_2] \quad (2)$$

$F(\alpha)$ indicates the changing rate of government adopting strategy A_1 . $F(\alpha) > 0$ represents that government will be more likely to intervene over time, whereas $F(\alpha) < 0$ means the contrary. Similarly, for enterprise strategies adjustment, the expected and overall benefits, and the replication dynamic equation are Equations (3) and (4).

$$\begin{cases} W_{B1} = \alpha G_1 + R_2 - C_3 \\ W_{B2} = -\alpha P_1 - \gamma C_4 + R_3 \\ W_B = \beta W_{B1} + (1 - \beta)W_{B2} \end{cases} \quad (3)$$

$$F(\beta) = \frac{\partial \beta}{\partial t} = \beta(W_{B1} - W_B) = \beta(1 - \beta)(W_{B1} - W_{B2}) = \beta(1 - \beta)[\alpha(G_1 + P_1) + \gamma C_4 + R_2 - C_3 - R_3] \quad (4)$$

In the same way, we can obtain the calculation results of projects, as in Equations (5) and (6).

$$\begin{cases} W_{D1} = \alpha G_2 + \beta R_5 + R_4 - C_5 \\ W_{D2} = R_6 \\ W_D = \gamma W_{D1} + (1 - \gamma)W_{D2} \end{cases} \quad (5)$$

$$F(\gamma) = \frac{\partial \gamma}{\partial t} = \gamma(W_{D1} - W_D) = \gamma(1 - \gamma)(W_{D1} - W_{D2}) = \gamma(1 - \gamma)[\alpha G_2 + \beta R_5 + R_4 - C_5 - R_6] \quad (6)$$

2.2. Evolutionary Equilibria of the System

Each player's long-term equilibrium strategy can be determined by stability analysis. According to the method proposed by Lv [44], the evolutionary stability strategy (ESS) of the differential equation system can be obtained from the local stability analysis of the Jacobian matrix of the system. By comparing the benefit for government with two strategies, we find that $R_1 > G_1 + G_2 + C_1$ should be satisfied.

In the absence of government intervention, the decisions made by enterprises and projects in terms of strategy are based on profit maximization. Therefore, $R_2 + G_1 > C_3$ and $G_2 + R_4 + R_5 > C_5$ should be met. From Equations (2), (4) and (6), the Jacobian matrix of the system is Equation (7).

$$\begin{cases} F(\alpha) = \frac{\partial \alpha}{\partial t} = \alpha(1 - \alpha)[- \beta(P_1 + G_1) - \gamma G_2 + R_1 + P_1 - C_1 + C_2] \\ F(\beta) = \frac{\partial \beta}{\partial t} = \beta(1 - \beta)[\alpha(G_1 + P_1) + \gamma C_4 + R_2 - C_3 - R_3] \\ F(\gamma) = \frac{\partial \gamma}{\partial t} = \gamma(1 - \gamma)[\alpha G_2 + \beta R_5 + R_4 - C_5 - R_6] \end{cases} \quad (7)$$

In Equation (7), if $F(\alpha) = F(\beta) = F(\gamma)$, the local stable equilibrium points are: $E_1 = (0, 0, 0)$, $E_2 = (1, 0, 0)$, $E_3 = (0, 1, 0)$, $E_4 = (0, 0, 1)$, $E_5 = (1, 1, 0)$, $E_6 = (1, 0, 1)$, $E_7 = (0, 1, 1)$, $E_8 = (1, 1, 1)$. Any starting point must be in a three-dimensional space $V \{(\alpha, \beta, \gamma) | 0 \leq \alpha \leq 1, 0 \leq \beta \leq 1, 0 \leq \gamma \leq 1\}$, as must its evolution range. According to evolutionary game theory, the equilibrium point satisfying all the eigenvalues of the

Jacobian matrix is the evolutionary stable point (ESS). Thus, we calculate the Jacobian matrix of the dynamic equation, as in Equation (8).

$$J = \begin{bmatrix} \frac{\partial F(\alpha)}{\partial \alpha} & \frac{\partial F(\alpha)}{\partial \beta} & \frac{\partial F(\alpha)}{\partial \gamma} \\ \frac{\partial F(\beta)}{\partial \alpha} & \frac{\partial F(\beta)}{\partial \beta} & \frac{\partial F(\beta)}{\partial \gamma} \\ \frac{\partial F(\gamma)}{\partial \alpha} & \frac{\partial F(\gamma)}{\partial \beta} & \frac{\partial F(\gamma)}{\partial \gamma} \end{bmatrix} \quad (8)$$

Particularly, $\frac{\partial F(\alpha)}{\partial \alpha} = (1 - 2\alpha)[- \beta(P_1 + G_1) - \gamma G_2 + R_1 + P_1 - C_1 + C_2]$; $\frac{\partial F(\alpha)}{\partial \beta} = -\alpha(1 - \alpha)(P_1 + G_1)$; $\frac{\partial F(\alpha)}{\partial \gamma} = -\alpha(1 - \alpha)G_2$; $\frac{\partial F(\beta)}{\partial \alpha} = \beta(1 - \beta)(G_1 + P_1)$; $\frac{\partial F(\beta)}{\partial \beta} = (1 - 2\beta)[\alpha(G_1 + P_1) + \gamma C_4 + R_2 - C_3 - R_3]$; $\frac{\partial F(\beta)}{\partial \gamma} = \beta(1 - \beta)C_4$; $\frac{\partial F(\gamma)}{\partial \alpha} = \gamma(1 - \gamma)G_2$; $\frac{\partial F(\gamma)}{\partial \beta} = \gamma(1 - \gamma)R_5$; $\frac{\partial F(\gamma)}{\partial \gamma} = (1 - 2\gamma)[\alpha G_2 + \beta R_5 + R_4 - C_5 - R_6]$.

The corresponding eigenvalues can be obtained by substituting eight equilibrium points into the Jacobian matrix, as shown in Table 4.

Table 4. Evolutionary game payoff matrix.

Equilibrium Points	Eigenvalues		
	λ_1	λ_2	λ_3
$E_1(0,0,0)$	$R_1 + P_1 - C_1 + C_2$	$R_2 - C_3 - R_3$	$R_4 - C_5 - R_6$
$E_2(1,0,0)$	$-R_1 - P_1 + C_1 - C_2$	$G_1 + P_1 + R_2 - C_3 - R_3$	$G_2 + R_4 - C_5 - R_6$
$E_3(0,1,0)$	$-G_1 + R_1 - C_1 + C_2$	$-R_2 + C_3 + R_3$	$R_5 + R_4 - C_5 - R_6$
$E_4(0,0,1)$	$-G_2 + R_1 + P_1 - C_1 + C_2$	$C_4 + R_2 - C_3 - R_3$	$-R_4 + C_5 + R_6$
$E_5(1,1,0)$	$G_1 R_1 + C_1 - C_2$	$-G_1 - P_1 - R_2 + C_3 + R_3$	$G_2 + R_5 + R_4 - C_5 - R_6$
$E_6(1,0,1)$	$G_2 - R_1 - P_1 + C_1 - C_2$	$G_1 + P_1 + C_4 + R_2 - C_3 - R_3$	$-G_2 - R_4 + C_5 + R_6$
$E_7(0,1,1)$	$-G_1 - G_2 + R_1 - C_1 + C_2$	$-C_4 - R_2 + C_3 + R_3$	$-R_5 - R_4 + C_5 + R_6$
$E_8(1,1,1)$	$G_1 + G_2 - R_1 + C_1 - C_2$	$-G_1 - P_1 - C_4 - R_2 + C_3 + R_3$	$-G_2 - R_5 - R_4 + C_5 + R_6$

To analyze the symbols of eigenvalues corresponding to different equilibrium points without losing generality, it is assumed that $R_1 - G_1 - G_2 - C_1 + C_2 > 0$, $R_2 + G_1 - C_3 - R_3 + P_1 + C_4 > 0$, $R_2 + G_1 - C_3 - R_3 + P_1 + C_4 < 0$, $G_2 + R_4 + R_5 - C_5 - R_6 > 0$, $G_2 + R_4 + R_5 - C_5 - R_6 < 0$. The evolutionary game stability strategy is discussed, and the path of tripartite evolution is analyzed in three cases. Table 5 shows the results of the stability analysis of the system equilibrium points.

Table 5. Local stability equilibrium points.

Equilibrium Points	Case 1				Case 2				Case 3			
	λ_1	λ_2	λ_3	Stability	λ_1	λ_2	λ_3	Stability	λ_1	λ_2	λ_3	Stability
$E_1(0,0,0)$	+	+	+	Saddle	+	+	−	Unstable	+	−	−	Unstable
$E_2(1,0,0)$	−	+	+	Unstable	−	+	−	Unstable	−	−	−	ESS
$E_3(0,1,0)$	+	−	+	Unstable	+	−	−	Unstable	+	+	−	Unstable
$E_4(0,0,1)$	+	+	−	Unstable	+	+	+	Saddle	+	−	+	Unstable
$E_5(1,1,0)$	−	−	+	Unstable	−	−	−	ESS	−	+	−	Unstable
$E_6(1,0,1)$	−	+	−	Unstable	−	+	+	Unstable	−	−	+	Unstable
$E_7(0,1,1)$	+	−	−	Unstable	+	−	+	Unstable	+	+	+	Unstable
$E_8(1,1,1)$	−	−	−	ESS	−	−	+	Unstable	−	+	+	Saddle

Notes: It is the stable point when all of eigenvalues are negative. It is the unstable point when the eigenvalues are positive. The saddle point occurs when the eigenvalues are both positive and negative at the same time.

Case 1: When $R_1 - G_1 - G_2 - C_1 + C_2 > 0$, $R_2 + G_1 - C_3 - R_3 + P_1 + C_4 > 0$, and $G_2 + R_4 + R_5 - C_5 - R_6 > 0$ is satisfied, that is, the benefits of three parties participating in the promotion of SCS are higher than those without participation. At this moment, $E_8 = (1, 1, 1)$ is the stable point, and the evolutionary strategy is (intervention, promotion, supported). In this case, the government will increase incentives for enterprises and projects

that support the development of SCS. Enterprises that do not promote SCS will be severely punished. The three parties will eventually show a stable state in E_8 .

Case 2: When $R_1 - G_1 - G_2 - C_1 + C_2 > 0$, $R_2 + G_1 - C_3 - R_3 + P_1 + C_4 > 0$, and $G_2 + R_4 + R_5 - C_5 - R_6 < 0$ is satisfied, that is, government and enterprises benefit greatly in intervening the promotion of SCS. At this point, $E_5 = (1, 1, 0)$ is the stable point of the system (ESS), and the evolutionary strategy (intervention, promotion, unsupported). In this case, the active policy has a further impact on the development of SCS. Enterprises can reap more benefits and achieve a higher social impact by actively promoting SCS. Even if the projects do not support the development of SCS, a stable state can be established through the joint promotion of the government and enterprises.

Case 3: When $R_1 - G_1 - G_2 - C_1 + C_2 > 0$, $R_2 + G_1 - C_3 - R_3 + P_1 + C_4 < 0$, and $G_2 + R_4 + R_5 - C_5 - R_6 < 0$ is satisfied, that is, the tripartite initial returns are negative. At this point, $E_1 = (1, 0, 0)$ is the stable point of the system (ESS), and the evolutionary strategy (intervention, non-promotion, unsupported). In this case, the development of SCS will be hindered because of the low benefits of enterprises and projects.

Based on the stability analysis of the equilibrium point of government, enterprises and projects, the following conclusions are drawn: (1) The intervention of government is an important guarantee of tripartite equilibrium, but it is not the fundamental factor. (2) The intervention of government has a significant impact on enterprise strategy choice but has little impact on projects. (3) Projects is the executor of SCS, whose strategy choice will not change the evolution trend.

3. Results

3.1. Numerical Simulation Based on System Dynamics (SD)

3.1.1. Construction of the System Dynamics Model

Based on the functional relationship of cumulative variables, state variables, auxiliary variables and external variables given by Equations (1)–(6), a system dynamics model can be established as in Figure 2. The probability of the three game parties adopting an aggressive strategy is denoted as three cumulative variables. The three state variables are used to represent the changing rate of the probability of a positive strategy being adopted by them, respectively. The cumulative variables are determined by the state variables. The auxiliary variables are the expected revenue when the three parties adopt different strategies, including W_{A1} , W_{A2} , W_{B1} , W_{B2} , W_{D1} , W_{D2} . The external variables are listed in Table 1.

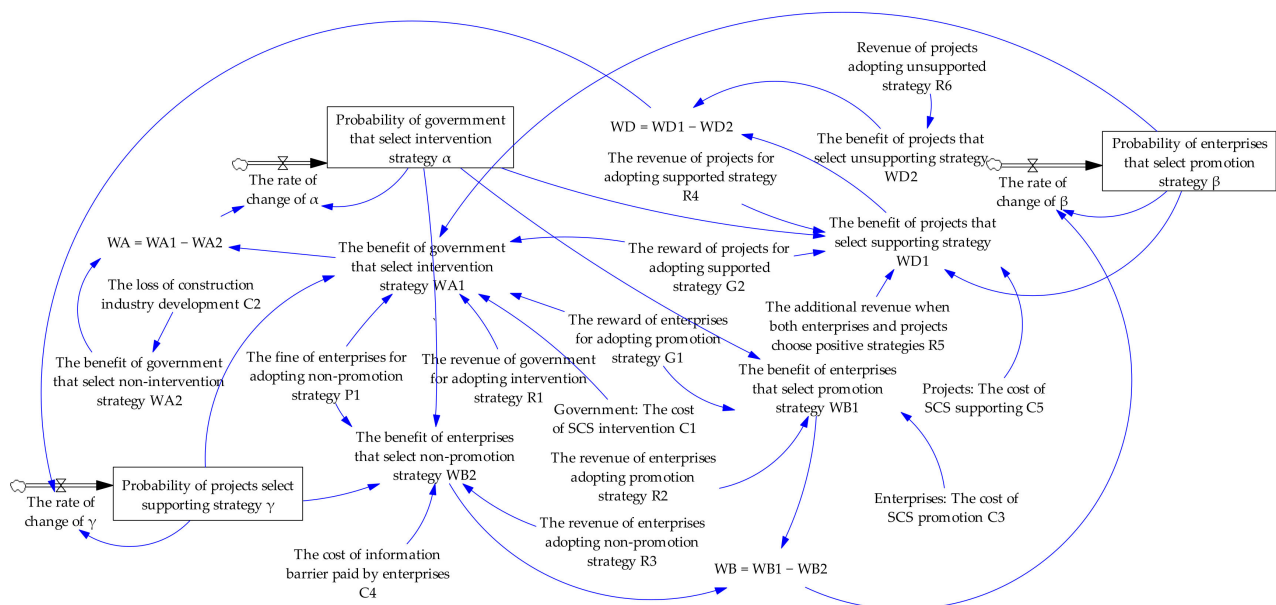


Figure 2. SD evolving a game simulation model for SCS promotion.

The benefits function of different plays in the evolutionary game under various strategies can be used to identify the link between auxiliary variables and external variables. The benefit of this simulation model is not its realism, but rather its ability to depict the internal regularity of change. Therefore, it does not necessitate extremely precise outcomes [45]. The accuracy of the parameter settings is less crucial than the correctness of the structural design [46]. The external variables involved in the SD model's basis values are taken from the literature. All the simulation parameters allow for the sensitivity of the change of the relevant element to government, enterprise, and project strategic decisions. As long as the parameter settings meet the prerequisites of the theoretical analysis, the proportions may change, and the modeling results need not be constant. The external variables involved in the SD model are from the literature. The setting of all simulation parameters considers the sensitivity of each relevant factor change to the strategic choices of three parties. Numerical simulation needs to consider the actual situation, so three groups of data are determined.

BAU1, BAU2, BAU3 are the three-equilibrium state for comparative analysis. The three scenarios are used to verify the stability of equilibrium strategies $S_1 = (1, 1, 1)$, $S_2 = (1, 1, 0)$, $S_3 = (1, 0, 0)$, respectively. They are also used to verify the sensitivity of strategic factors affecting government, enterprises, and projects.

3.1.2. System Evolution Equilibrium

For simulation, Vensim PLE is used, with a cycle of 15, an initial time of 0, a termination time of 15, and a step length of 0.125. The probability of a positive strategy choice is the fundamental measurement standard. According to the analysis above, we know that 0 and 1 can represent the initial strategy choices. None of them would like to modify the current, but if one or more individuals make minor adjustments, the equilibrium state will shift. We set the initial strategy with a probability of 0.5 to make the system change, and the initial state of evolutionary game system is (0.5, 0.5, 0.5). For the purposes of this paper, intermediate variables are assumed to be positive, as shown in Table 6. To analyze the change of the three-party strategy selection, 0 and 1 are used to represent the positive and negative strategy. The simulation results when the three parties adopt positive strategies are analyzed as follows.

Table 6. Parameter settings.

Name of Parameter	Parameter Value		
	BAU1	BAU2	BAU3
P_1	4.0	2.5	2.5
G_1	2.5	2.0	2.0
G_2	2.5	1.0	1.5
R_1	5.0	5.0	5.0
C_1	1.5	1.5	1.5
C_2	2.0	2.0	2.0
C_3	2.0	3.5	3.5
C_4	2.0	2.0	2.0
R_2	3.5	4.5	1.5
R_3	4.0	4.0	4.0
C_5	1.5	1.5	1.5
R_4	1.5	1.0	1.5
R_5	2.5	1.5	2.0
R_6	2.5	2.5	3.0

In scenario BAU1, the intervention strategy of government is highlighted, and the punishment for enterprises that do not promote SCS is increased. Meanwhile, the incentives for enterprises and projects supporting the development of SCS are increased. The evolution equilibrium point is (1, 1, 1), and the evolution process is shown in Figure 3. By increasing incentives, the government can guide enterprises and projects to actively promote the development of SCS. Government intervention is an important guarantee for realizing the

balance of benefit for the three parties. It will promote enterprises and support project, and finally realize the stable balance of the three parties.

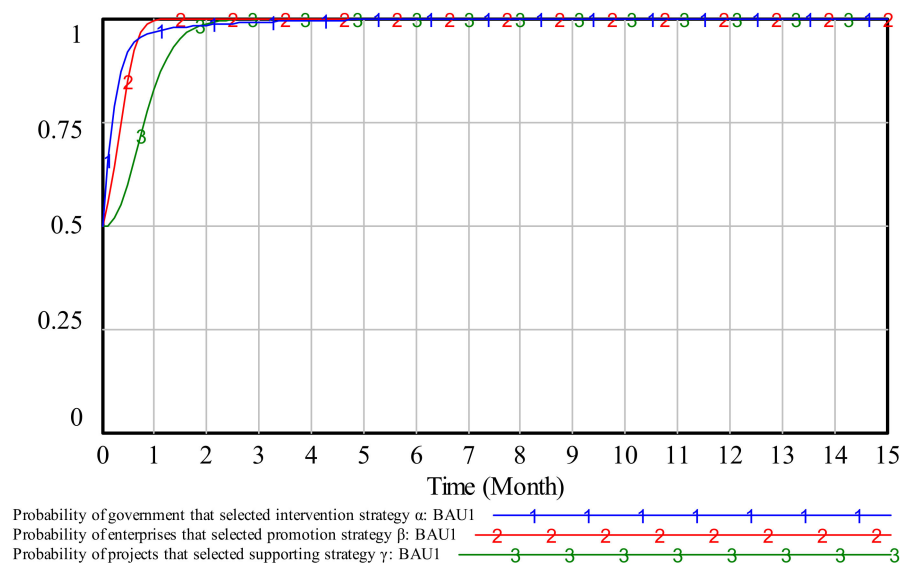


Figure 3. Stability test of the equilibrium point (1,1,1).

In Scenario BAU2, the promotion strategy of enterprises is highlighted. Enterprises can improve the management level, production capacity and benefit increase through support from projects. The evolution equilibrium point is (1,1,0), and the evolution process is shown in Figure 4. The active promotion of enterprises has a far-reaching influence on the development of SCS. Enterprises gain more benefits by improving their social status and create a virtuous cycle. In this section, even if the project does not support SCS, a balanced state can be established through the joint promotion of government and enterprises. In the long term, projects will change its strategy with the social environment and the development of SCS.

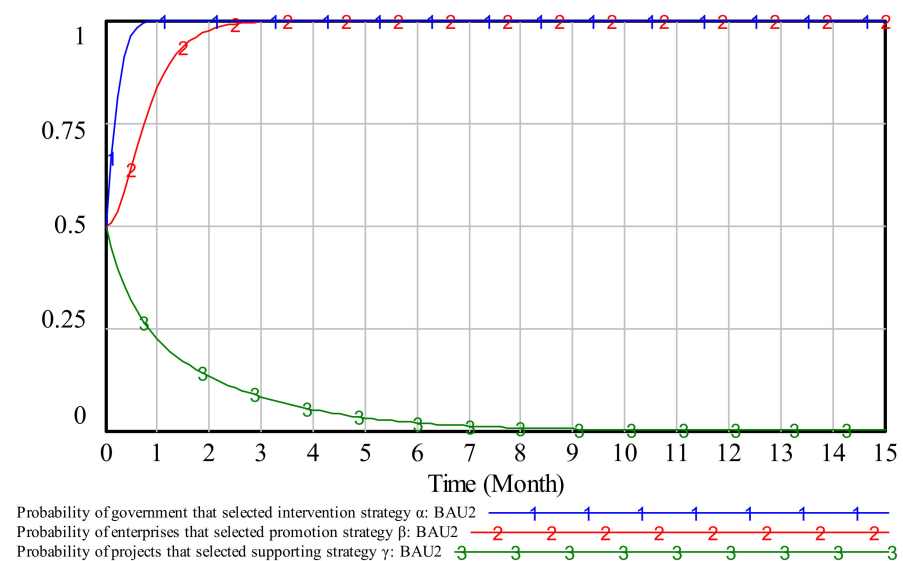


Figure 4. Stability test of the equilibrium point (1,1,0).

In Scenario BAU3, the supporting strategy of projects is highlighted. Projects will have more benefits in the award process if they adopt a supporting strategy. The extra revenue will be given to them if enterprises adopt a promotion strategy. Besides, corporate reputation will damage if enterprises adopt a contrary strategy. The evolution equilibrium

point is (1,0,0), and the evolution process is shown in Figure 5. The project is the practical side of SCS, but it lacks certain leading power and is limited in many places. If government does not intervene in time, it will affect the strategic choice of the project. Therefore, it is necessary for it to intervene in the early development of SCS. However, it is significant for the long-term benefit and healthy development of SCS to enterprise joint effort and pay attention to the needs of all projects.

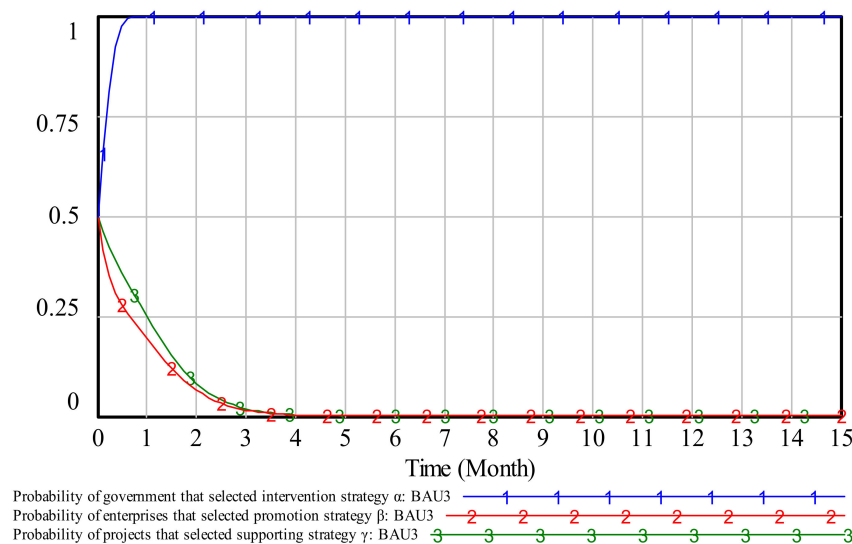


Figure 5. Stability test of the equilibrium point (1,0,0).

The result shows that in BAU1, when the benefit of government is positive, they tend to adopt an intervention strategy and thereby advance the adoption of a promotion strategy by enterprises. To put it another way, government intervention can effectively promote the development of SCS. However, enterprise promotion is required to guide the projects to a condition of continuous improvement.

3.1.3. Impact of Government Intervention on System Equilibrium

When $\alpha = 1$, the trend for enterprises to choose a promotion strategy does not change. β and γ both increase with a similar range of influence, as in Figure 6. This confirms that government intervention is efficient under the equilibrium state (1,1,1). Thus, in a BAU1 scenario, the support of government determines the speed of SCS advancement.

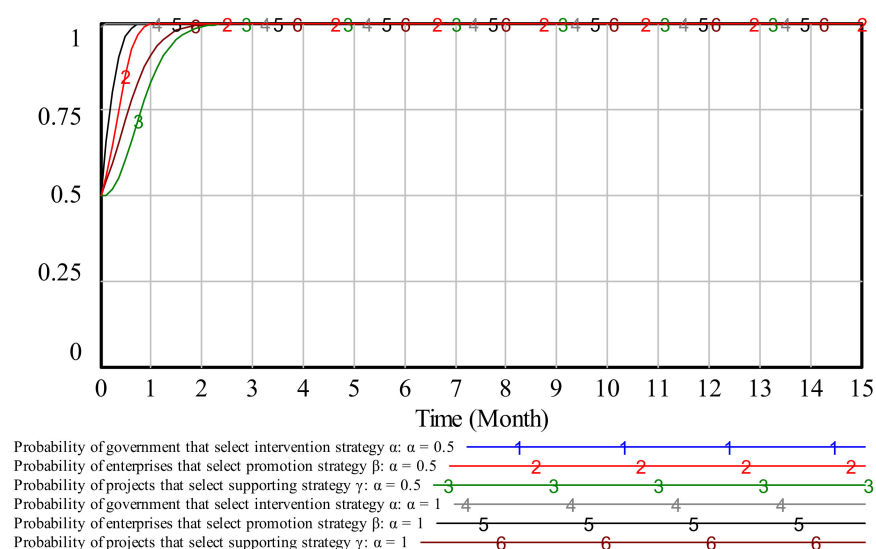


Figure 6. In BAU1, the evolution of enterprises and projects under government intervention.

In BAU2, when $\alpha = 1$, β shows a minimal increase from line 2 to line 5. Projects eventually gravitate toward a non-supported strategy, although the rate of change slows (from line 3 to line 6), as in Figure 7. The fundamental issue is that the technology offered by enterprises does not improve project utility. However, intervention measures have boosted the desire of enterprises to innovate in SCS technology, and the probability of projects adopting positive strategies has increased as well. As a result, in BAU2, enterprise promotion measures should be performed, and the influence of SCS advice on the system may be greater.

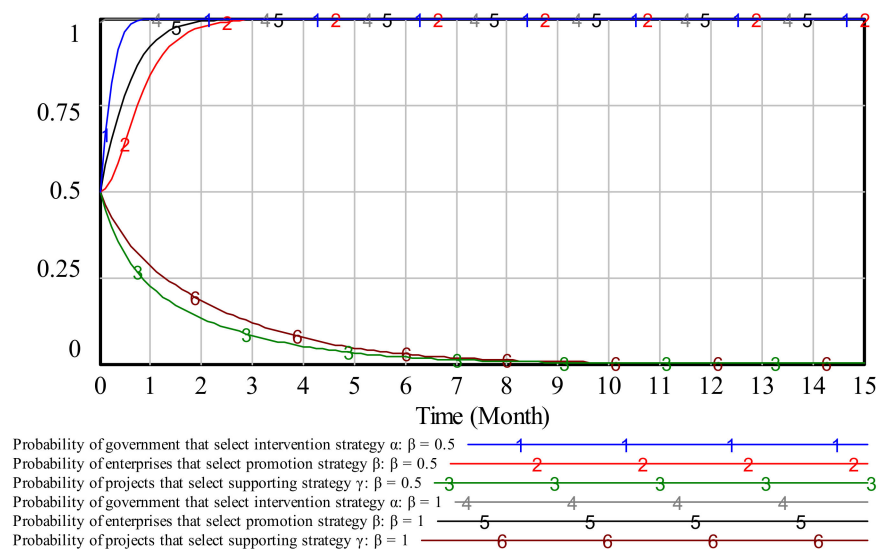


Figure 7. In BAU2, the evolution of enterprises and projects under government intervention.

In BAU3, when $\alpha = 1$, the system equilibrium state changes from (1,0,0) to (1,1,1). The probability of enterprises adopting a promotion strategy shows a great increase (from line 2 to line 5 and from line 3 to line 6), as in Figure 8. Government intervention strategies play an important role in promoting the development of SCS. Under the guidance and help of government policies, enterprises will gradually adopt promotion strategies to promote the development of technologies related to SCS. The project feels the government's involvement and the active promotion of enterprises, and will also change strategies as the environment changes with the development of SCS.

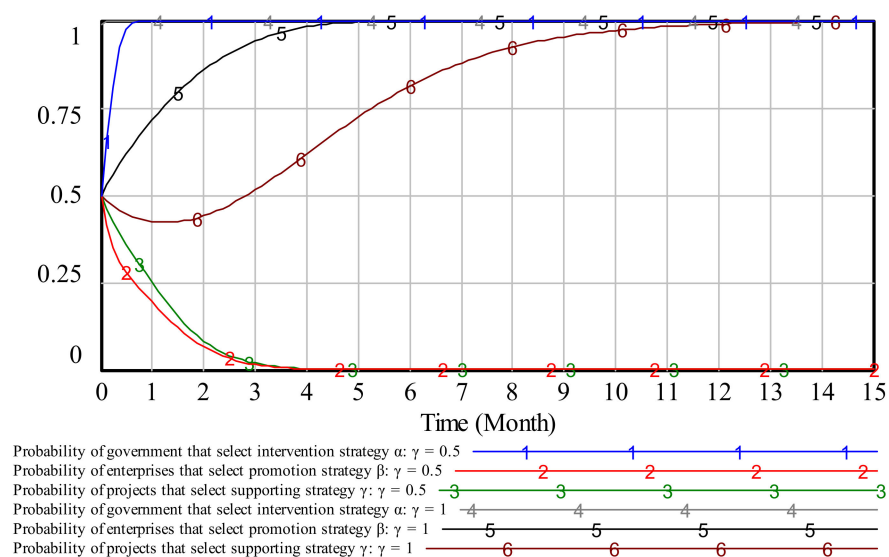


Figure 8. In BAU3, the evolution of enterprises and projects under government intervention.

3.2. Sensitivity Analysis

According to the analysis of the equilibrium point in Table 5, the values of the external variables determine whether a strategy combination is in equilibrium [47]. The development of SCS is based on the intervention of the government. In BAU1, government action has a minor impact on businesses and initiatives. The sensitivity analysis therefore focuses on the elements that influence how enterprises and projects participate in promoting SCS. Table 6 demonstrates that the exogenous variables that influence enterprise strategy choices include G_2 , R_2 , and R_6 , while the exogenous variables affecting the choice of project strategy are P_1 , G_1 , C_3 , and R_2 . Figures 9–11 depict the evolution of enterprise strategy selection as a result of several exogenous variables, while Figures 12–15 represent the strategic evolution of the project.

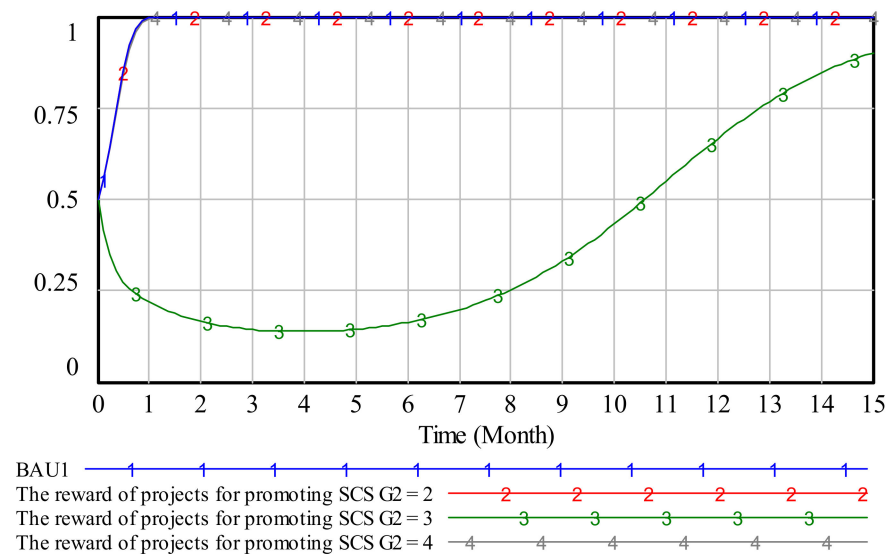


Figure 9. Impact of G_2 on the enterprise strategy selection in the BAU1 scenario.

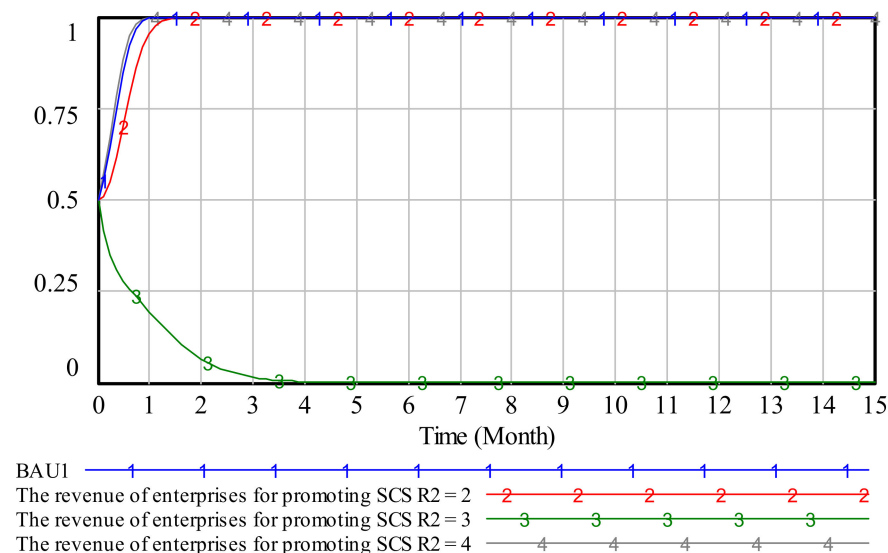


Figure 10. Impact of R_2 on the enterprise strategy selection in the BAU1 scenario.

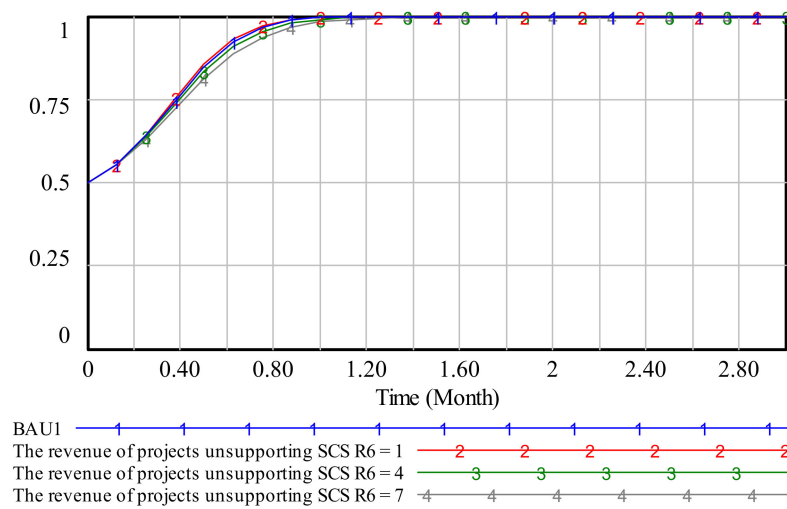


Figure 11. Impact of R_6 on enterprise strategy selection in the BAU1 scenario.

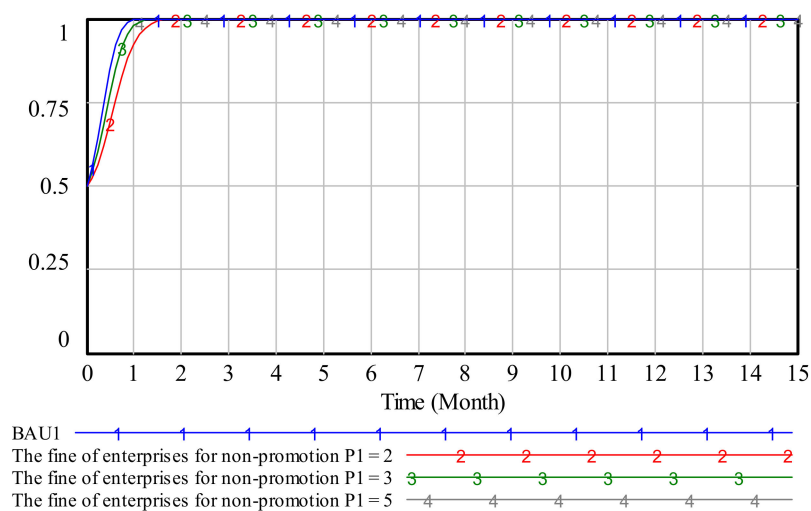


Figure 12. Impact of P_1 on enterprise strategy selection in the BAU1 scenario.

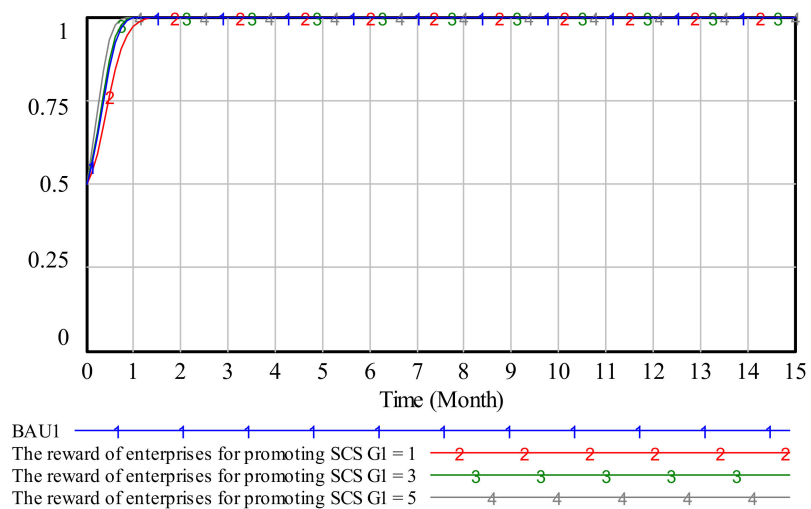


Figure 13. Impact of G_1 on project strategy selection in the BAU1 scenario.

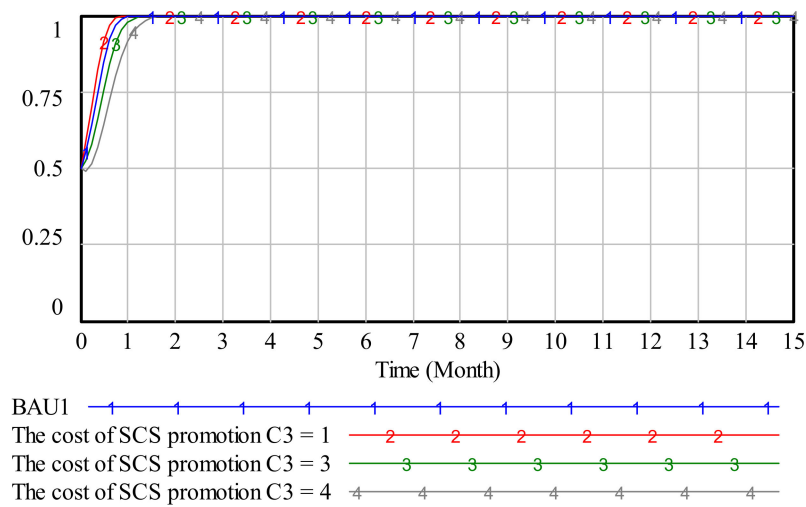


Figure 14. Impact of C_3 on project strategy selection in the BAU1 scenario.

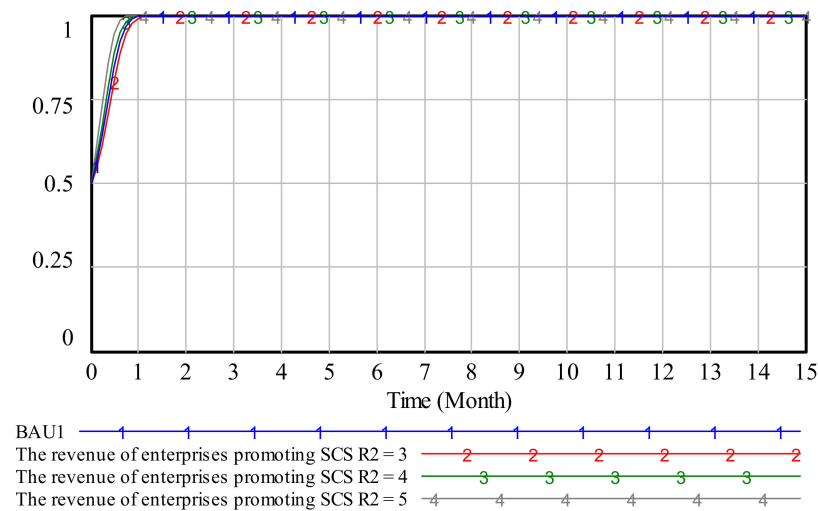


Figure 15. Impact of R_2 on project strategy selection in the BAU1 scenario.

3.2.1. The Impact of Exogenous Variables on Enterprise Strategy Choices

Figure 9 shows that the impact of the reward of projects for promoting SCS G_2 on enterprises willingness to promote SCS refers to the related project strategy rather than a continuous increase. When $G_2 = 3$, the probability that enterprises will choose to move forward with SCS decreases, but given enough time, they will change their strategic choices over time in this case (line 3). As the project gains increase in the process of promoting SCS, i.e., when $G_2 = 4$, it will reverse the probability of promoting SCS for the enterprise (line 4). It can be seen that, firstly, the final choices of enterprises is positive, which means that they will eventually advance the SCS. Secondly, enterprises will consider the benefits of projects in the process when making strategy choices, and decision-makers will shift their strategies according to the business environment and take the benefits of subordinate projects as an important reference basis.

Figure 10 shows the impact on the revenue for enterprises adopting promotion strategy R_2 on enterprise willingness to promote SCS. Similar to the effect of G_2 on the enterprise strategy choice, R_2 is also in a more suitable value range, which can improve the probability of enterprises choosing active strategies. When $R_2 = 2$, the probability that an enterprise chooses an active strategy increases from 0.5 to 1 (line 2) and shows an opposite trend as R_2 increases to 3. However, the enthusiasm of enterprises to promote SCS has increased significantly again when $R_2 = 4$ (line 3 and line 4). This shows that in the process of promoting

the development of SCS, the revenue of enterprises will bottleneck at a certain level, and the willingness of enterprises will continue to increase after breaking the bottleneck.

Figure 11 shows the impact of the revenue of projects adopting unsupported strategy R_6 on enterprise willingness to promote SCS. Combining lines 1 to 4, the project does not support the revenue when the SCS is advanced, which will affect the motivation of the enterprises. Because the projects' return under the negative strategy has a small effect on the enterprises, the experimental difference is increased in this paper to obtain a more significant effect. The higher the benefits projects obtained when it is not involved in promoting SCS, the less likely it is that enterprises will support the development (line 4). SCS can only be advanced when the benefits it brings to the project are greater than a threshold value.

3.2.2. The Impact of Exogenous Variables on Project Strategy Choices

Figure 12 shows the fine of enterprises for adopting non-promotion strategy P_1 on projects willingness to promote SCS. The fine refers to the penalty measures taken by government for the lack of wisdom in the inspection stage when enterprises do not support the SCS. From the results of the numerical simulation, the probability of project choosing to support strategy shows an "inverted U" shape with the increase of the penalty. When $P_1 = 4$, the fastest rate of change from 0.5 to 1 (line 1) was observed for projects supporting SCS. The penalty is too low to play a supervisory effect, the penalty is too high to play a counterproductive role. Thus, it can be seen that enterprises and projects can impact each other when taking different types of measures. According to the stakeholder theory, the common interests of both need to be considered in the promotion of SCS.

Figures 13–15 show G_1 , C_3 , and R_2 on project willingness to promote SCS, who have a direct relationship to the enterprise rather than the projects. The three variables represent the reward, cost and revenue of enterprises for adopting the promotion strategy. According to the numerical simulation result, the willingness of projects to support is related to the benefits of enterprises when promoting SCS. The higher the benefits and the lower the costs of enterprises in promoting SCS, the higher the probability of projects supporting their development. From this, it can be obtained that when formulating the policy of promoting SCS, the government should use encouragement as the main means by which to reduce the development cost, so that enterprises and projects can participate in the development across all aspects.

4. Discussion and Implications

4.1. Discussion

The Smart Construction Site Development (SCSD) system involves multiple stakeholders such as the government, enterprises, and projects. According to the stakeholder theory [48], the convergence state of the system can be disturbed by internal and external factors. Each factor has a varied impact on the benefits and costs of different players [36]. Therefore, if one of the contributing factors or participant strategies changes, the system will fluctuate and approach a new equilibrium state. Through numerical simulation, important factors affecting the evolution and balance of the system can be obtained. As demonstrated through the findings in this paper, the key drivers of the SCSD system include penalties and incentives for government intervention strategies, and the benefits and costs of companies advancing SCS.

According to the results, the sustainable development of SCS needs to be realized from the aspects of market, organization, motivation and guarantee. In the construction market, government guidelines should be adhered to, and the application of SCS to government projects and demonstration enterprises should be prioritized in order to cultivate pilot projects. Besides, key cities must be made priority areas for the development of SCS technology, and the number of pilot projects must be agreed on. At the same time, the application of smart construction should be increased to improve the quality of project construction and to refine the level of construction, so as to realize the transformation, upgrading and

sustainable development of the construction industry. In terms of organization, sound organizational structures should be established and improved. Via government authorities, a Smart Site Leadership Group should be set up to formulate the overall plan of SCS development. Besides, a development center and expert committee will be established by the Smart Site Leadership Group to cooperate with the introduction of relevant policies and standards and to establish mechanism measures. Using the SCS platform as a tool, a three-tier linkage management structure for government, enterprises and projects should be established. The sustainable development of SCS also needs a source of motivation, with the government providing external motivation in terms of policy and training guidance, and enterprises and projects providing internal motivation in terms of technology, talent, management and operation. In terms of guarantee, the government needs to give financial and taxation policy support, including providing preferential loans, preparing smart site development fund, reforming value added tax (VAT), adjusting consumption tax, and improving corporate income tax. After this, it should improve laws and regulations, introduce corresponding technical standards, management standards, interface standards, etc., in order to achieve horizontal and vertical multi-faceted system protection.

In addition, regulatory protection is also indispensable. According to the results of numerical simulation, the government has an important role to play in the process of promoting SCS. The government can provide guarantees for relevant parties by strengthening the supervision of policy and regulation implementation and by establishing a supervision platform so as to realize the whole process of supervision and management of SCS projects and to effectively ensure the quality and safety of the projects while reducing supervision costs by using information technology.

4.2. Implications

A multi-agent model is required to investigate the effectiveness of government intervention. On this basis, the influence of each original strategy and external factor is systematically analyzed in order to identify the key factors so as to provide reasonable policy recommendations.

The core stakeholders of SCS are government, enterprises and projects. Based on the three parties, an evolutionary system is constructed and numerical simulations are performed to obtain three stable and balanced strategy combinations. In actuality, the analysis of these three strategies can lead to three equilibria situations. BAU3 represents the primary stage of SCS development, with the government as the main body, and the willingness of enterprises and projects to participate is not strong. BAU2 represents the transitional stage of SCS development. With the continuous advancement of government intervention policies, enterprises have begun to join the team of developing SCS. BAU1 represents the mature stage of SCS development. With the joint participation of the government, enterprises and projects, the development of SCS continues to deepen.

In the mature stage of SCS development, it is more important to take appropriate measures so as to improve the high-quality development of the construction industry rather than to improve the benefits of enterprises and projects in the development process. To maintain a smooth operation of the building market, the government must enact regulatory measures. Furthermore, the government should encourage enterprises to take the lead in addressing the social responsibilities engendered by the technological revolution, such as enhancing the property rights protection system and supporting market-based allocation. Government intervention is an important guarantee for the tripartite balance and is an important factor affecting and restricting the promotion of enterprises and projects. The project is the final consumer of the smart construction site, but it lacks dominance. Its strategic choice will have a certain impact on the tripartite equilibrium, but it will not change the evolution trend. Steady states can also be achieved with the simultaneous adoption of aggressive strategies by governments and businesses, as shown in BAU2. After the government intervenes, companies can implement smart construction sites through mandatory projects, but this is not a lasting solution. Therefore, when the government

formulates policies, it needs to focus on analyzing the factors that affect the promotion of enterprises, and actively guide the strategic choices of projects through enterprises, which is key to achieving a balanced state.

5. Conclusions and Recommendations

5.1. Conclusions

As an emerging product under the rapid development of information, SCS provides a good opportunity for the transformation of the construction industry. In the continuous development, a series of problems have been exposed, which need to be solved by certain measures. The game relationship between SCS stakeholders is employed as the research object in this study, and a three-party game model is used to analyze each game player's equilibrium strategy and the SCS promotion system. System dynamic simulations are also conducted to investigate the impact of relevant external variables on the equilibrium stability. There are four primary conclusions with theoretical and practical implications for advancing government regulation and promoting active participation of enterprises and projects in the development of SCS.

1. In the SCS promotion system, there are three possible equilibrium states. When government intervenes to increase penalties and incentives, both enterprises and projects are more inclined to adopt a promotion strategy. When the benefits of developing SCS being higher for enterprises, the government supports enterprises to establish an equilibrium, while the projects stay in the negative strategy for the time being. When the benefits of developing SCS are higher for projects, enterprises tend to take a negative strategy, the government prefers to take an intervention strategy, and projects tend not to develop SCS.
2. In the evolution of the SCSD system, the government intervention is the key to achieving a tripartite balance. By raising the initial probability of government intervention from 0.5 to 1, the final equilibrium for three scenarios is (1,1,1). Thus, the initial decision of the government determines the development prospect of SCS. Government adoption of an intervention strategy will have the same impact on the strategic choices of enterprises and projects.
3. In BAU1, the strategy choice of enterprises is related to the benefits associated with the project. The impact of government incentives for projects on the willingness of enterprises to advance SCS is not absolutely continuous, but is related to the strategic choice of the project. There is a bottleneck in the revenue of enterprises to advance SCS in influencing their strategic choices, and when this bottleneck is broken, their willingness grows. The revenue of projects when it does not support SCS then affects the motivation of enterprises to advance SCS development.
4. In BAU1, the strategic choice of the project is closely related to enterprises. The penalty for not promoting SCS has an "inverted U" shape in relation to the probability of choosing a support strategy for the project. The payoffs, costs and benefits of promoting SCS development have a more direct effect on the strategy choice of the project. Moreover, they have a positive effect on the strategy choice of the project, while the costs of the enterprise have the opposite effect.

5.2. Recommendations

The equilibrium strategy of an SCS promotion system is composed of government, enterprises, and projects, and has an influence on important factors on the system strategy equilibrium. Although it offers some valuable recommendations for the development and optimization of SCS promotion policies, there are a few limitations to be aware of.

Firstly, the payoff functions of the game participants are to be improved throughout model creation. Refine government spending in terms of penalties and incentives, for example, and the benefits of the project to promote SCS are related to public support. Secondly, the model does not take into account the characteristics of construction enterprises, whose authority has a significant impact on the benefits generated by the promotion of

SCS. Thirdly, uncertainty and spillover effects are key factors affecting SCS propulsion, and future research needs to embed such factors in the propulsion system of multiple intelligences involved in SCS to facilitate a more accurate identification of their roles in the system evolution process. Finally, government needs to make continuous efforts in promoting SCS, and how to dilute the government's effectiveness and achieve market regulation is the basis for high quality development of the construction industry. So far, the literature has focused on the relationship between government and the construction market from a qualitative perspective, and future research should shift more toward quantitative analysis.

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