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Incentive Mechanism of BIM Application in Prefabricated Buildings Based on Evolutionary Game Analysis

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Abstract: Prefabricated buildings have become a key area promoted in the new urbanization. Implementing BIM is one of the crucial supports for accelerating the development of prefabricated buildings. In order to effectively promote the development of BIM+ prefabricated buildings, this paper establishes an evolutionary game model between the government and prefabricated construction enterprises. The replication dynamic equation is employed to analyze the strategy choices of both participants, and the Matlab simulation is adopted to explore the evolution process of enterprises to actively use BIM. Results show that the application of new technologies can be effectively promoted by increasing the unit price of carbon trading, enlarging the tax rate difference, advancing technology, improving the level of enterprise effort, and enhancing social awareness to reduce the payment-to-income ratio of enterprises using BIM. Additionally, reasonable administrative measures, policy subsidies and fines will also positively affect government incentives and the strategy choice of enterprises using BIM. Therefore, a reasonable government incentive system can promote the development of BIM+ prefabricated buildings to a certain extent.

Keywords: prefabricated buildings; government incentives; evolutionary game; BIM; environmental benefits

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1. Introduction

The traditional building model is difficult to adapt to the development of society due to its long construction cycle, poor design flexibility, and serious pollution. Prefabricated buildings, with small impact on the environment and high utilization of resources in the entire building life cycle, show good performance in the construction industry [1–3]. During the COVID-19 epidemic, the advantages of prefabricated buildings were fully manifested in the building of related medical security facilities with building information modeling (BIM), which provided a guarantee for the fight against the epidemic [4].

It was pointed out in relevant documents on carbon peaking and carbon neutrality that it is necessary to vigorously develop energy-saving and low-carbon buildings and to continuously improve energy-saving standards for new buildings [5]. With the application and development of BIM, the market environment and construction applications of prefabricated buildings have been expanded and highly valued by the Chinese government. Digital green innovation management is the core of low-carbon intelligent development of prefabricated construction enterprises [6]. The introduction of BIM enables prefabricated buildings to effectively establish resource plans, control capital risks, save energy, reduce pollution and improve resource utilization in the stages of design, construction and use. By optimizing the design, errors and link losses can be reduced, thereby reducing costs [7]. However, due to the imperfect domestic standard system and difficulty of software operation, it is difficult for BIM to be widely used in prefabricated buildings [8–10]. Therefore, the government has to issue policies and measures related to the application of BIM to encourage prefabricated construction enterprises to improve their abilities to promote the development of prefabricated buildings with BIM [11].

The government fulfills its responsibility to promote the development of prefabricated buildings through subsidies. However, without innovation at the technical management level, development relying only on subsidies is unsustainable. In addition to government strategies, the decision-making of prefabricated construction enterprises is also affected by their actual development and psychological behavior. A series of energy conservation and environmental protection policies will also affect the strategy choices of different subjects.

This paper analyzes the relationship between the government and prefabricated construction enterprises. Meanwhile, considering factors such as cost, risk perception, incentive effect, environmental regulation effect and other influencing factors, an evolutionary game model is constructed to analyze the strategy choices of both parties under the influence of different parameters. Then, Matlab is applied to carry out the numerical simulation and analyze how government incentives enable enterprises to use BIM technology in assembly building management. Finally, the feasibility of promoting BIM technology in prefabricated buildings through government incentive policies is analyzed, which provides a basis for the government to formulate reasonable policies.

2. Related Work

The government and prefabricated construction enterprises are the two main bodies that directly affect the development of the prefabricated construction industry. In the existing literature, the government's incentive policies on both sides of "government-prefabricated construction enterprises" have been explored. However, there are certain limitations. Firstly, many research are conducted mainly from the perspective of government financial subsidies. However, as it is known, promoting prefabricated buildings through subsidies without innovation at the technical management level is not sustainable. Once there are no government subsidies, high-cost prefabricated buildings will not survive. Secondly, it is argued in existing literature that the government should encourage enterprises to innovate components. However, at present, component innovation is complex and requires a long research period, which is a great challenge for the development of prefabricated buildings. Thirdly, previous studies rarely considered the factors influencing the decision-making of the government and enterprises and ignored the correlation between parameters. Government income and enterprise income are closely related. The decisions of enterprises are not only affected by government strategies, but also by their actual development. In addition, some energy conservation and environmental protection policies will also have an impact on the strategy choices of both sides. Therefore, this paper reviews relevant literature from three aspects: incentive policies for prefabricated buildings, the application of BIM technology in prefabricated buildings and the environmental benefits of prefabricated buildings.

2.1. Incentive Policies for Prefabricated Buildings

The top five factors that promote prefabricated construction in China are technology lock-in, incentive policies, standardization, cost and entrepreneurial awareness [12]. Government subsidies, credit support and tax breaks in incentive policies help transfer green building technology and play a crucial role in promoting prefabricated construction development [13]. The existing prefabrication incentive policies can be divided into seven categories, i.e., mandatory policies, financial support, tax incentives, building area incentives, loan support, land supply and noneconomic incentives [14].

In the selection of incentive strategies, government incentives for the development of prefabricated buildings include the establishment of special funds, preferential tax policies and financial subsidy mechanisms [15]. Research show that reputational incentives, increased rewards and punishments, increased consumer acceptance and reduced component costs can accelerate the realization of the evolutionary stable strategy (ESS) in a two-participant game model. Therefore, incentive policies should also focus on consumers, prefabricated component manufacturers and contractors [16]. In terms of incentive strategies, some scholars believe that reducing the construction cost of prefabricated buildings is a better choice than government subsidies, and measures such as levying environmental taxes can promote low-carbon and environmental protection of prefabricated buildings [17]. Moreover, it is confirmed that government fiscal taxation and punishment policies can effectively promote manufacturers' use of prefabricated components [18]. Corporate cooperation, such as job support and welfare training, also plays an important role in promoting the development of the prefabricated construction industry [19].

Scholars have also proposed that financial subsidies play a leading role in the early stages of prefabricated housing construction [20]. In order to maximize the effect of government subsidies, they theoretically determined the scope, amount and time of subsidies through evolutionary game model simulation analysis [21].

2.2. Application Research of BIM in Prefabricated Buildings

BIM can be used to facilitate cooperation and information sharing between project teams, which simplifies the process of prefabricating buildings and improves the quality, efficiency and sustainability of components and the overall construction. It can also optimize the allocation of human and material resources in prefabricated building construction, thereby reducing the waste of resources [22,23].

In recent years, a lot of research have been conducted on the application of BIM in the management of prefabricated buildings. Compared with traditional design methods, collaborative design using BIM has been tested to be more effective [24]. The real-time automatic calculation software in the BIM platform can effectively optimize the design and reduce costs [25]. Meanwhile, through the application of BIM and FRID technologies, the integration and visualization of precast concrete building component information would be realized, which could ensure the real-time and traceability of information. This is conducive to optimizing design and maximizing economic benefits [26]. Moreover, results of research on the management system of prefabricated building materials show that it is more effective if the system is established based on BIM, which can reduce both the cost and the warehouse occupation [27,28]. BIM also has an impact on green environmental protection and sustainable development, for it can be used to analyze the influencing factors of building annual energy consumption and provide important information for green building design [29]. Since the BIM platform can simulate sunlight, lighting, ventilation, humidity, etc., the government can obtain the carbon emission trend by analyzing the carbon footprint of the PC building when a prefabricated building project model is established with BIM [30].

2.3. The Environmental Benefits of Prefabricated Buildings

Prefabricated buildings have become the development trend of the current construction industry owing to their advantages of high quality, energy saving, environmental protection, labor saving and time-saving [31]. In the context of rural revitalization, prefabricated buildings have many environmental benefits in terms of carbon emissions, energy consumption, material consumption, and waste generation compared with in-situ buildings [32].

Under the dual background of severe ecological environment damage and scarcity of natural resources, the economic development model at the expense of the environment is becoming increasingly unsustainable. Promoting prefabricated buildings can not only improve the production model of the construction industry, but also reduce the environmental burden brought by the development of the construction industry [33]. The environmental benefits of prefabricated buildings have always been a focus of academic research. The main advantage of prefabricated building construction is its positive impact on the environment [34]. Many scholars have discovered the advantages of prefabricated buildings in energy conservation and emission reduction through experiments and data analysis [35].

Precast concrete can improve construction efficiency, energy saving and environmental protection, which has been proved by the analysis of thermal performance evaluation [36]. Additionally, compared with traditional buildings in environmental performance, resource energy consumption, health damage and ecosystem damage of prefabricated buildings can be reduced by 35.82%, 6.61% and 3.47%, respectively [37]. Although the carbon emission of prefabricated buildings increases in the production and transportation stage, it decreases significantly in the construction stage [38]. Therefore, many scholars propose methods including levying environmental taxes, limiting the profit of traditional cast-in-place units, and enhancing the energy-saving and environmental protection performance of prefabricated buildings to accelerate the industrialization of prefabricated buildings from the perspective of environmental regulation, so that consumers are more aware of the environmental benefits, thereby promoting the development of prefabricated buildings [38].

3. Evolutionary Game Model for BIM Application

In previous studies, many problems have been solved with the evolutionary game model. For example, Qing'e Wang et al. [39] considered many factors, such as cooperation willingness, sharing level, income distribution and punishment mechanisms, when establishing green technology innovation in construction enterprises. Chen et al. [40] found that government carbon taxes were more effective in encouraging low-carbon manufacturing than government subsidies for low-carbon technologies. Hongxia Sun et al. [41] found that the initial value of evolutionary games can predict the trend of future changes, and government subsidies should be limited within a reasonable range. Based on previous studies, this paper establishes an evolutionary game model in which the government encourages prefabricated construction enterprises to use BIM technology. Various factors such as the correlation between government and enterprise income, social benefits, environmental effects, and punishment mechanisms are taken into consideration, and the impacts of factors such as the enterprise income-payment ratio, carbon tax difference, carbon transaction unit price, initial ratio and government subsidy level on decision-making are also analyzed in depth.

3.1. Model Establishment

The subjects of the evolutionary game model in this paper are the government and the prefabricated construction enterprises. Both are bound by rationality and the capability of learning. They will adjust their own strategies according to the other side's strategy so as to achieve equilibrium. For the government, it can provide special subsidies and tax incentives to enterprises that use BIM, impose penalties on enterprises that do not use BIM, and macrocontrol the environmental trading market to promote the development of the industry. Then, corresponding social and environmental benefits can be generated and total management costs reduced. Strategies of the government are "incentive" and "non-incentive", and the corresponding probabilities are x ($0 \leq x \leq 1$) and $1 - x$. For prefabricated construction enterprises, the use of BIM will lead to increased costs, but at the same time, they can receive corresponding preferential policies, incremental economic benefits and brand value. Therefore, their strategies are "using BIM" and "not using BIM", and the corresponding probabilities are y ($0 \leq y \leq 1$) and $1 - y$.

The profit and loss parameters of the model and their explanations are shown in Table 1. The free carbon emission allocated by the local government g to an enterprise e is c [42], and the actual emission of the enterprises is Q. The carbon emission transaction unit price is q, which is determined by the market. When the enterprise does not use BIM to optimize the design, the carbon emission is Q_d, ($Q_d > c$). When the enterprise uses BIM to optimize the design, the carbon emission is Q_u, ($Q_u < c$). When the emission $Q >$ c, the enterprise has to purchase the carbon emission of Q-c in the carbon trading market, and the expenditure is E_d ($E_d = q(Q_d - c)$). When the emission $Q < c$, the enterprise can sell the carbon emission of $c - Q$ in the carbon trading market, and the revenue is E_u ($E_u = q(c - Q_u)$) [43].

Table 1. Profit and loss parameter values of the participants.

Profit and Loss Parameters	Parameter Description
w	Enterprise work efficiency
a	Enterprise average profit without using BIM
o	Other factors
β	Enterprise profit coefficient
γ	Cost coefficient
t	Investment degree
α	Government subsidy coefficient
m	Government-enterprise income correlation coefficient when the enterprise uses BIM
n	Government-enterprise income correlation coefficient when the enterprise does not use BIM
λ	Sensitivity coefficient of the enterprise to risk
σ	Difference between the cost paid by the enterprise and the reference spread value
ρ	Risk aversion of the enterprise
C_{ag}	Administrative cost of the government's incentive strategy
C_{ig}	Government subsidy costs when enterprises use BIM
P_{ug}	Economic benefits obtained by the government when enterprises use BIM
P_{dg}	Economic benefits obtained by the government when enterprises do not use BIM
S_g	Social benefits obtained by the government when enterprises use BIM
P_{ue}	Economic benefits obtained by the enterprises when use BIM
P_{de}	Economic benefits obtained by the enterprises when not using BIM
C_e	Extra cost of the enterprises when using BIM
S_e	Social benefits obtained by the enterprises when using BIM
E_d	Carbon trading amount (expenditure) when enterprises do not use BIM
E_u	Carbon trading amount (income) when enterprises use BIM
T_u	Environmental taxes levied by the government when enterprises use BIM
T_d	Environmental taxes levied by the government when enterprises do not use BIM
A	Risk perception of enterprises on whether to use BIM
F	Fines for enterprises not implementing government incentives
M	$M = \beta(hw + a + o) - P_{de} + S_e + q(Q_d - Q_u) - 0.5\gamma(th)^2 + t_d Q_d - t_u Q_u - \lambda\sigma^\rho$
N	$N = F - C_{ag}$
s	enterprise payment to income ratio, $s = \frac{0.5\gamma(th)^2 + \lambda\ \sigma^\rho}{\beta(hw+a+o) - P_{de} + S_e + q(Q_d - Q_u) + t_d Q_d - t_u Q_u}$

The extra cost of using BIM is C_e ($C_e = 0.5\gamma(th)^2$), and the effect is R_{ue} ($R_{ue}(h) = hw + a + o$) [44]. The enterprise profit is P_{ue} ($P_{ue} = \beta R_{ue}(h)$), and the social benefits (such as reputation, brand, etc.) brought to the enterprise are S_e. If the enterprise does not use BIM, the enterprise profit is P_{de}. Among them h is the enterprise effort level, w is the enterprise work efficiency, a is the average enterprise profit without using BIM, β is the enterprise profit coefficient, γ is the cost coefficient, t is the investment degree and o refers to other factors.

The administrative cost (promulgation of corresponding laws and regulations, publicity, supervision, education, etc.) for the government to encourage enterprises to use BIM is C_{ag}. When an enterprise uses BIM, the government gives subsidies according to the effect of the enterprise's use of BIM, and the amount of subsidy is C_{ig} ($C_{ig} = \alpha[R_{ue}(h) - R_{ue}(0)] = \alpha hw$). The government revenue is P_{ug} $\left(P_{ug} = mP_{ue}\right)$, which is related to the enterprise profit. Additionally, the government's social benefits (environment, etc.) are S_g. When the enterprise does not use BIM, the government's revenue is P_{dg} $\left(P_{dg} = nP_{de}\right)$. The government's incentive policy is mandatory, so when the enterprise does not implement it, a fine F must be paid [45]. Among them α is the government subsidy coefficient, m is the government-enterprise income correlation coefficient when the enterprise uses BIM, and n is the government-enterprise income correlation coefficient when the enterprise does not use BIM.

The local government levies environmental tax T_u ($T_u = t_u Q_u$) at a lower tax rate t_u from enterprises that choose to use BIM, and levies environmental tax T_d ($T_d = t_d Q_d$) at a higher tax rate t_d from enterprises that do not choose to use BIM.

Whether an enterprise chooses to use BIM is essentially a question of risk choice. If the enterprise is risk-averse, its risk perception is A $(A = \lambda\sigma^{\rho})$ [17]. λ is the sensitivity coefficient of the enterprise to risk, σ is the difference between the cost paid by the enterprise and the reference spread value, and ρ is the risk aversion of the enterprise.

In the process of an evolutionary game, both players no longer choose the stable Nash equilibrium solution as the final strategy selection structure, but gradually explore the evolutionarily stable equilibrium solution through a process of continuous comparison, learning and imitation.

According to the above analysis assumptions, the game payment matrix is established, as shown in Tables 2 and 3.

Table 2. Game payment matrix of government and prefabricated construction enterprises.

Both Sides of the Game		Prefabricated Construction Enterprises	
		Use BIM y	**Not Use BIM** $1-y$
Government	incentive x	$P_{ug} + S_g + T_u - C_{ag} - C_{ig}$, $C_{ig} + P_{ue} + S_e + E_u - C_e - T_u - A$	$P_{dg} + T_d - C_{ag} + F$, $P_{de} - T_d - E_d - F$
	No incentive $1 - x$	$P_{ug} + T_u + S_g$, $P_{ue} + S_e + E_u - C_e - T_u - A$	$P_{dg} + T_d$, $P_{de} - E_d - T_d$

Table 3. Game payment matrix of government and prefabricated construction enterprises (Concrete parameter representation).

Both Sides of the Game		Prefabricated Construction Enterprises	
		Use BIM y	**Not Use BIM** $1-y$
Government	incentive x	$m\beta(hw + a + o) + S_g + t_u Q_u - C_{ag} - \alpha hw$, $\alpha hw + \beta(hw + a + o) + S_e + q(c - Q_u) - 0.5\gamma(th)^2 - t_u Q_u - \lambda\sigma^{\rho}$	$P_{dg} + t_d Q_d - C_{ag} + F$, $P_{de} - t_d Q_d - q(Q_d - c) - F$
	No incentive $1 - x$	$m\beta(hw + a + o) + t_u Q_u + S_g$, $\beta(hw + a + o) + S_e + q(c - Q_u) - 0.5\gamma(th)^2 - t_u Q_u - \lambda\sigma^{\rho}$	$P_{dg} + t_d Q_d$, $P_{de} - q(Q_d - c) - t_d Q_d$

The benefits are U_{11} and U_{12}, respectively when the government chooses "incentive" or "non-incentive" strategies. The average benefits of the government are U_1, and the corresponding calculated values are as follows:

$$U_{11} = y\left[m\beta(hw + a + o) + S_g + t_u Q_u - C_{ag} - \alpha hw\right] + (1 - y)\left(P_{dg} + t_d Q_d - C_{ag} + F\right) \tag{1}$$

$$U_{12} = y\left[m\beta(hw + a + o) + t_u Q_u + S_g\right] + (1 - y)\left(P_{dg} + t_d Q_d\right) \tag{2}$$

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

The benefits are U_{21} and U_{22}, respectively when an enterprise chooses to "use BIM" or "not use BIM" strategies. The average benefits of the government are U_2, and the corresponding calculated values are as follows:

$$\begin{aligned} U_{21} = x&\left[\alpha hw + \beta(hw + a + o) + S_e + q(c - Q_u) - 0.5\gamma(th)^2 - t_u Q_u - \lambda\sigma^{\rho}\right] \\ &+(1 - x)\left[\beta(hw + a + o) + S_e + q(c - Q_u) - 0.5\gamma(th)^2 - t_u Q_u - \lambda\sigma^{\rho}\right] \end{aligned} \tag{4}$$

$$U_{22} = x[P_{de} - t_d Q_d - q(Q_d - c) - F] + (1 - x)[P_{de} - q(Q_d - c) - t_d Q_d] \tag{5}$$

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

Based on the benefit Equations (1)–(6) of the government and the prefabricated construction enterprises, the replicative dynamic equations of the government and the enterprises can be obtained, which are:

$$F(x) = \frac{dx}{dt} = x(U_{11} - U_1) = x(1-x)\left[-y(\alpha hw + F) + F - C_{ag}\right] \quad (7)$$

$$F(y) = \frac{dy}{dt} = y(U_{21} - U_2) = y(1-y)\Big[\beta(hw + a + o) - P_{de} + S_e + q(Q_d - Q_u) - 0.5\gamma(th)^2 + t_d Q_d - t_u Q_u - \lambda\sigma^\rho + x(\alpha hw + F)\Big] \quad (8)$$

According to Equations (7) and (8), in order to bring the game model to equilibrium, the replication dynamic equations of the government and enterprises must meet the following requirements: $F(x) = 0$, $F(y) = 0$, then the following solutions can be obtained:

$$x = 0,\ x = 1, y^* = \frac{F - C_{ag}}{\alpha hw + F} \quad (9)$$

$$y = 0, y = 1, x^* = -\frac{\beta(hw + a + o) - P_{de} + S_e + q(Q_d - Q_u) - 0.5\gamma(th)^2 + t_d Q_d - t_u Q_u - \lambda\sigma^\rho}{\alpha hw + F} \quad (10)$$

3.2. ESS Analysis of the Government and Enterprises

For the government, if $y = \frac{F-C_{ag}}{\alpha hw+F}$, $F(x) = 0$, no matter what the value of x is, the government is in a stable state.

If $y \neq \frac{F-C_{ag}}{\alpha hw+F}$, then $x = 0,\ x = 1$ is the possible stable point of the government strategy replication dynamic equation. At this point, the partial derivative of $F(x)$ with respect to x can be obtained:

$$\frac{\partial F(x)}{\partial x} = (1-2x)\left[-y(\alpha hw + F) + F - C_{ag}\right] \quad (11)$$

When $\frac{\partial F(x)}{\partial x} < 0$, the evolutionary stability strategy is satisfied, obviously $\alpha hw + F > 0$. Therefore, $F - C_{ag}$ will be discussed. When $F - C_{ag} < 0$, $y > \frac{F-C_{ag}}{\alpha hw+F}$, then $x = 0$ is the stable point; when $F - C_{ag} > 0$ and $y > \frac{F-C_{ag}}{\alpha hw+F}$, then $x = 0$ is the stable point; and when $F - C_{ag} > 0$ and $y < \frac{F-C_{ag}}{\alpha hw+F}$, then $x = 1$ is the stable point.

For enterprises, if $x = -\frac{\beta(hw+a+o)-P_{de}+S_e+q(Q_d-Q_u)-0.5\gamma(th)^2+t_dQ_d-t_uQ_u-\lambda\sigma^\rho}{\alpha hw+F}$, $F(y) = 0$, no matter what the value of y is, the enterprise is in a stable state. On the other hand, $y = 0$ and $y = 1$ are the possible stable points of the enterprise strategy replication dynamic equation. At this point, the partial derivative of $F(y)$ with respect to y can be obtained:

$$\frac{\partial F(y)}{\partial y} = (1-2y)\Big[\beta(hw + a + o) - P_{de} + S_e + q(Q_d - Q_u) - 0.5\gamma(th)^2 + t_d Q_d - t_u Q_u - \lambda\sigma^\rho + x(\alpha hw + F)\Big] \quad (12)$$

When $\frac{\partial F(y)}{\partial y} < 0$, the evolutionary stable strategy (ESS) is satisfied, obviously $\alpha hw + F > 0$. Therefore, $\beta(hw + a + o) + S_e + q(Q_d - Q_u) + t_d Q_d - t_u Q_u - 0.5\gamma(th)^2 - \lambda\sigma^\rho - P_{de}$ will be discussed.

When $\beta(hw + a + o) + S_e + q(Q_d - Q_u) + t_d Q_d - t_u Q_u - 0.5\gamma(th)^2 - \lambda\ \sigma^\rho - P_{de} > 0$, $x > -\frac{\beta(hw+a+o)-P_{de}+S_e+q(Q_d-Q_u)-0.5\gamma(th)^2+t_dQ_d-t_uQ_u-\lambda\sigma^\rho}{\alpha hw+F}$, then $y = 1$ is the stable point.

When $\beta(hw + a + o) + S_e + q(Q_d - Q_u) + t_d Q_d - t_u Q_u - 0.5\gamma(th)^2 - \lambda\ \sigma^\rho - P_{de} < 0$, $x > -\frac{\beta(hw+a+o)-P_{de}+S_e+q(Q_d-Q_u)-0.5\gamma(th)^2+t_dQ_d-t_uQ_u-\lambda\sigma^\rho}{\alpha hw+F}$, then $y = 1$ is the stable point.

When $\beta(hw + a + o) + S_e + q(Q_d - Q_u) + t_d Q_d - t_u Q_u - 0.5\gamma(th)^2 - \lambda\ \sigma^\rho - P_{de} < 0$, $x < -\frac{\beta(hw+a+o)-P_{de}+S_e+q(Q_d-Q_u)-0.5\gamma(th)^2+t_dQ_d-t_uQ_u-\lambda\ \sigma^\rho}{\alpha hw+F}$, then $y = 0$ is the stable point.

3.3. ESS Analysis of Both Participants

The above analysis shows that there are five equilibrium points in the replication dynamic equation, which are $(0,1)$, $B(0,0)$, $C(1,0)$, $D(1,1)$ and $E\left(-\frac{\beta(hw+a+o)-P_{de}+S_e+q(Q_d-Q_u)-0.5\gamma(th)^2+t_dQ_d-t_uQ_u-\lambda\sigma^{\rho}}{\alpha hw+F}, \frac{F-C_{ag}}{\alpha hw+F}\right)$.

Let $M = \beta(hw+a+o) - P_{de} + S_e + q(Q_d - Q_u) - 0.5\gamma(th)^2 + t_dQ_d - t_uQ_u - \lambda\sigma^{\rho}$, $N = F - C_{ag}$.

The stability of the equilibrium point of the evolutionary system can be judged by the Jacobian matrix. When the equilibrium point satisfies the determinant condition: $detJ > 0$, and the trace condition: $trJ < 0$, then this equilibrium point is the evolutionary stable strategy (ESS). For the above five equilibrium points, the values of the determinant and the trace are calculated, respectively. The results are shown in Table 4.

$$J = \begin{bmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} \end{bmatrix} = \begin{bmatrix} (1-2x)[-y(\alpha hw+F)+N] & -x(1-x)(\alpha hw+F) \\ y(1-y)(\alpha hw+F) & (1-2y)[M+x(\alpha hw+F)] \end{bmatrix} \quad (13)$$

Table 4. Expressions of the determinant and trace of the Jacobian matrix corresponding to the equilibrium point.

Equilibrium Point	*det*(*J*)	*tr*(*J*)
$(0,0)$	MN	$M+N$
$(0,1)$	$M(C_{ag}+\alpha hw)$	$-(C_{ag}+\alpha hw+M) = N-M-\alpha hw-F$
$(1,0)$	$-N(M+\alpha hw+F)$	$C_{ag}+\alpha hw+M = M+\alpha hw+F-N$
$(1,1)$	$-(C_{ag}+\alpha hw)(M+\alpha hw+F)$	$-(M+N)$
$\left(-\frac{M}{\alpha hw+F}, \frac{N}{\alpha hw+F}\right)$	$+$	0

The local stability analysis results are shown in Table 5.

Table 5. Local stability analysis results of the equilibrium points.

Case	Meaning	Condition	Local Equilibrium Point	*det*(*J*)	*tr*(*J*)	Equilibrium Result
Case 1	The incremental benefits brought by the use of BIM to prefabricated construction enterprises are less than the incremental costs and possible risks, and the difference between benefit and cost is greater than the government's incentive; the government penalty is large, but the administrative expenditure and subsidies are small, and the government incentive cost is low.	$(-M) > \alpha hw+F$ $0 < N < \alpha hw+F$	$(0,0)$	$-$	$-$	Unstable
			$(0,1)$	$-$	$+$	Unstable
			$(1,0)$	$+$	$-$	ESS
			$(1,1)$	$+$	$+$	Unstable
			$\left(-\frac{M}{\alpha hw+F}, \frac{N}{\alpha hw+F}\right)$	$+$	0	Unstable
Case 2	The incremental benefits brought by the use of BIM to prefabricated construction enterprises are less than the incremental costs and possible risks, and the difference between benefit and cost is greater than the government's incentive; the government penalty is small, but the administrative expenditure and subsidies are large, and the government incentive cost is high.	$(-M) > \alpha hw+\mathrm{F}$ $N < 0 < \alpha hw+F$	$(0,0)$	$+$	$-$	ESS
			$(0,1)$	$-$	uncertainty	Unstable
			$(1,0)$	$-$	uncertainty	Unstable
			$(1,1)$	$+$	$+$	Unstable
			$\left(-\frac{M}{\alpha hw+F}, \frac{N}{\alpha hw+F}\right)$	$+$	0	Unstable

Table 5. *Cont.*

Case	Meaning	Condition	Local Equilibrium Point	*det*(*J*)	*tr*(*J*)	Equilibrium Result
Case 3	The incremental benefits brought by the use of BIM to prefabricated construction enterprises are more than the incremental costs and possible risks; the government penalty is large, but the administrative expenditure and subsidies are small, and the government incentive cost is low.	$(-M) < 0 < \alpha hw + F$ $0 < N < \alpha hw + F$	$(0,0)$	$+$	$+$	Unstable
			$(0,1)$	$+$	$-$	ESS
			$(1,0)$	$-$	$+$	Unstable
			$(1,1)$	$-$	$-$	Unstable
			$\left(-\frac{M}{\alpha hw+F}, \frac{N}{\alpha hw+F}\right)$	$+$	0	Unstable
Case 4	The incremental benefits brought by the use of BIM to prefabricated construction enterprises are less than the incremental costs and possible risks, and the difference between benefit and cost is smaller than the government's incentive; the government penalty is large, but the administrative expenditure and subsidies are small, and the government incentive cost is low.	$0 < (-M) < \alpha hw + F$ $0 < N < \alpha hw + F$	$(0,0)$	$-$	uncertainty	Unstable
			$(0,1)$	$-$	uncertainty	Unstable
			$(1,0)$	$-$	uncertainty	Unstable
			$(1,1)$	$-$	uncertainty	Unstable
			$\left(-\frac{M}{\alpha hw+F}, \frac{N}{\alpha hw+F}\right)$	$+$	0	Central point
Case 5	The incremental benefits brought by the use of BIM to prefabricated construction enterprises are more than the incremental costs and possible risks; the government penalty is small, but the administrative expenditure and subsidies are large, and the government incentive cost is high.	$(-M) < 0 < \alpha hw + F$ $N < 0 < \alpha hw + F$	$(0,0)$	$-$	uncertainty	Unstable
			$(0,1)$	$+$	$-$	ESS
			$(1,0)$	$+$	$+$	Unstable
			$(1,1)$	$-$	uncertainty	Unstable
			$\left(-\frac{M}{\alpha hw+F}, \frac{N}{\alpha hw+F}\right)$	$+$	0	Unstable
Case 6	The incremental benefits brought by the use of BIM to prefabricated construction enterprises are less than the incremental costs and possible risks, and the difference between benefit and cost is smaller than the government's incentive; the government penalty is small, but the administrative expenditure and subsidies are large, and the government incentive cost is high.	$0 < (-M) < \alpha hw + F$ $N < 0 < \alpha hw + F$	$(0,0)$	$+$	$-$	ESS
			$(0,1)$	$-$	$-$	Unstable
			$(1,0)$	$+$	$+$	Unstable
			$(1,1)$	$-$	$+$	Unstable
			$\left(-\frac{M}{\alpha hw+F}, \frac{N}{\alpha hw+F}\right)$	$+$	0	Unstable

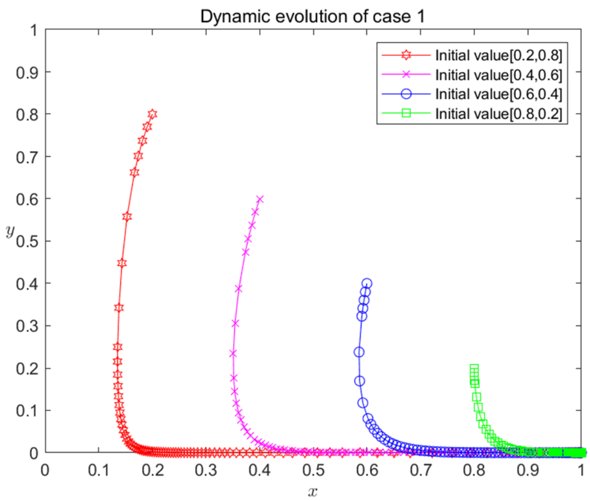
Analysis of enterprise strategy choices: From the analysis of Cases 1, 2, and 6, when $0 < (-M)$, that is, when the incremental benefits, such as economic benefits, brand value enhancement, resource and material conservation and environmental benefits, brought by the use of BIM to prefabricated construction enterprises are less than the incremental costs and possible risks, enterprises will evolve into a negative strategy of not using BIM. On the contrary, in Cases 3 and 5, when $(-M) < 0$, that is, when the incremental benefits brought by the use of BIM are less compared with cost increments and risks, prefabricated construction enterprises will evolve to a positive strategy of using BIM even with no government incentives. In other words, enterprises will use BIM consciously. Therefore, enterprises should reduce the cost of applying BIM technology, and the government should provide appropriate subsidies and preferential policies to reduce the risk of enterprises applying BIM technology.

Analysis of government strategy choices: In Cases 1 and 3, it can be obtained from $N > 0$, that is, $F > C_{ag}$, indicating that the government penalty is large, but the administrative expenditure and subsidies are small, and the government incentive cost is low. When enterprises do not use BIM, the government chooses to continue to incentivize, and the strategies of both parties evolve to the worst result of "incentive" and "not using BIM". When enterprises finally choose to use BIM, the government also dynamically adjusts its strategy accordingly until no incentive is given, and the strategies of both parties evolve to the optimal result of "no incentive" and "using BIM". In Cases 2, 5 and 6, it can be obtained from $N < 0$, that is, $< C_{ag}$, indicating the government penalty is small, but the administrative expenditure and subsidies are large, and the government incentive cost is high. When enterprises choose to use BIM, the government will naturally not incentivize it, and the strategies of both parties evolve towards the optimal result of "no incentive" and "using BIM". However, when enterprises choose not to use BIM, because of the high incentive cost, the government is overburdened and cannot maintain the incentives, the strategies of both parties evolve to the result of "no incentives" and "not using BIM", forming a vicious circle. Therefore, the government should choose a reasonable level of subsidy and penalty, which should not be too small to achieve the incentive effect nor too large to increase the burden on the government and hinder the long-term development of enterprises.

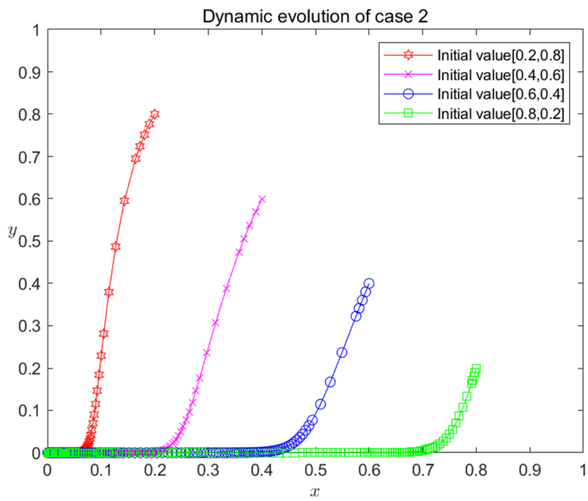
4. Simulation Research

4.1. Numerical Simulation and Result Analysis

In order to directly reflect the evolution path of the strategy choices of the government and prefabricated construction enterprises, this paper uses Matlab to carry out numerical simulation on the six cases in Section 3.3, and divides them according to the level of government subsidy and penalty, and the relationship between enterprise profit and expenditure. The initial values (x, y) of numerical simulation are respectively taken as $(0.2, 0.8)$, $(0.4, 0.6)$, $(0.6, 0.4)$ and $(0.8, 0.2)$. The dynamic evolution process of the game participants' strategy choices is shown in Figure 1.

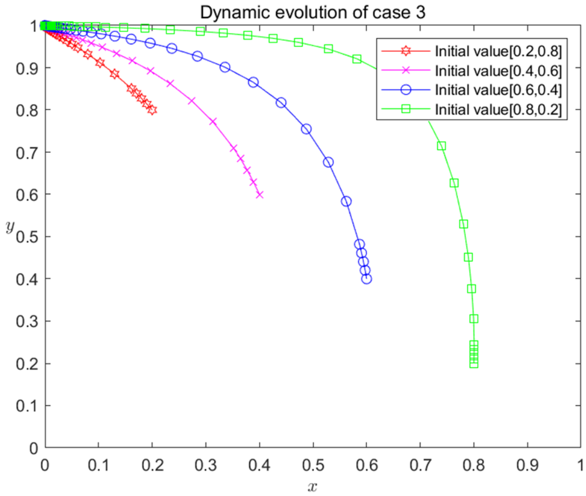


(**a**) Numerical simulation results of case 1

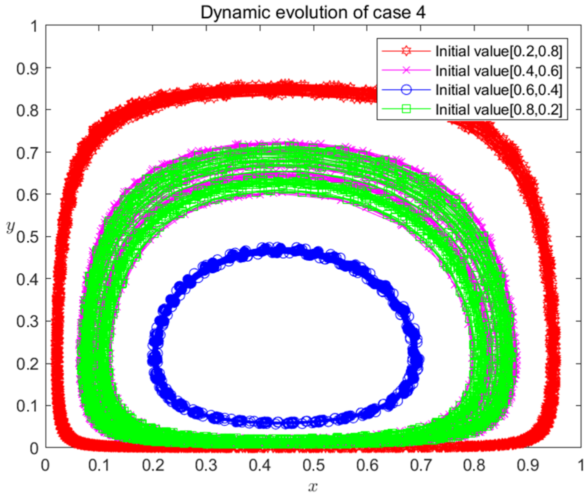


(**b**) Numerical simulation results of case 2

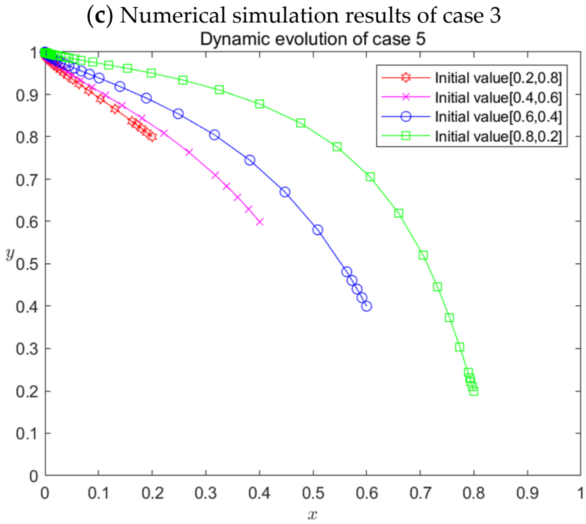
Figure 1. *Cont.*



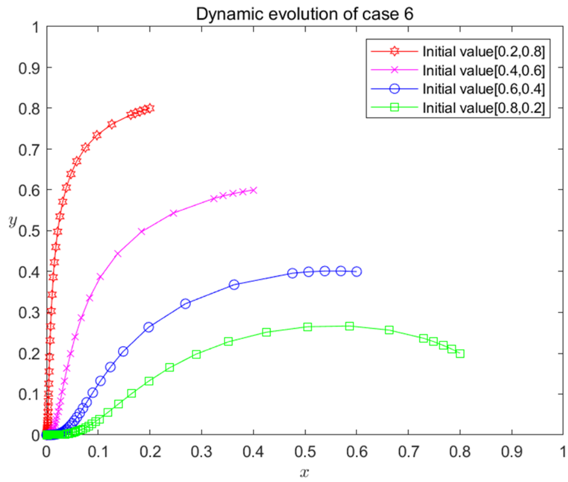
(**c**) Numerical simulation results of case 3



(**d**) Numerical simulation results of case 4



(**e**) Numerical simulation results of case 5



(**f**) Numerical simulation results of case 6

Figure 1. The dynamic evolution process of the game participants' strategy choices in various cases.

In Figure 1, it can be observed that the numerical simulation results in Case 1, Case 2 and Case 2 approached the points (1, 0), (0, 0), (0, 1) respectively, results in Case 5 and Case 6 tended to point (1, 0), (0, 0), and there was no stable point in Case 4, which are consistent with the results discussed in Section 3.2 by Jacobian matrix analysis.

It can be seen from the above analysis that the relationship between profit, cost and risk determines the strategy choice of an enterprise. Therefore, this paper further studies the impact of the relationship between profit, cost and risk of the evolution direction of whether enterprises use BIM when the government chooses the "non-incentive" strategy. Let the enterprise payment to income ratio is $s = \frac{0.5\gamma(th)^2+\lambda\ \sigma^{\rho}}{\beta(hw+a+o)-P_{de}+S_e+q(Q_d-Q_u)+t_dQ_d-t_uQ_u}$, s is taken as 0.2, 0.4, 0.6 and 0.8, respectively (take Case 3 as an example), and the simulation results are shown in Figure 2.

It can be seen from Figure 2 that the lower the payment-to-income ratio of the enterprise, the faster the two sides of the game tend to the stable strategy of (0,1). Factors that affect the expenditure of enterprises are the cost and risk perception of using BIM, so the cost of new technology applications can be reduced through scientific cost management. Factors that affect the profit of enterprises include enterprise effort level, social benefits, carbon tax rate, carbon trading price difference, etc. Therefore, environmental regulations can be issued to increase the carbon tax rate and the carbon trading unit price. Meanwhile, government incentives can enable enterprises to obtain higher social benefits and to be more active in using BIM, thereby improving their profits.

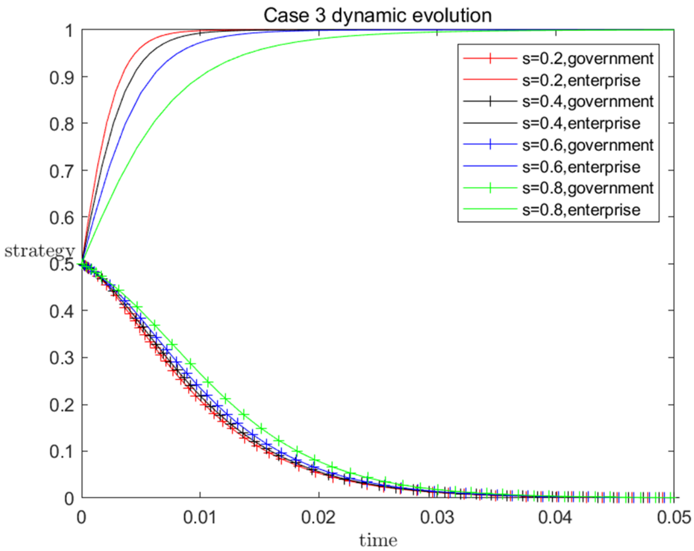


Figure 2. System evolution trajectory under different enterprise payment to income ratios.

According to the definition s of enterprise pay-to-ratio, P_{ue}, S_e, ΔE, ΔT are negatively correlated with s. Therefore, improving the economic and social benefits obtained by enterprises using BIM technology, and increasing the carbon trading unit price and carbon tax difference can shorten the time required for enterprises to choose to use BIM technology. P_{de}, C_e, A and s are positively correlated. Therefore, increasing subsidies to reduce the risks and costs of applying new technologies can shorten the time required for enterprises to choose to apply BIM technology.

Under the premise of Case 3, considering the influence of the carbon trading unit price, we can infer from *s* that the larger the unit price of carbon trading, the smaller the enterprise payment-to-income ratio and the shorter the evolutionary stable strategy (0,1). The Matlab numerical simulation results are shown in Figure 3.

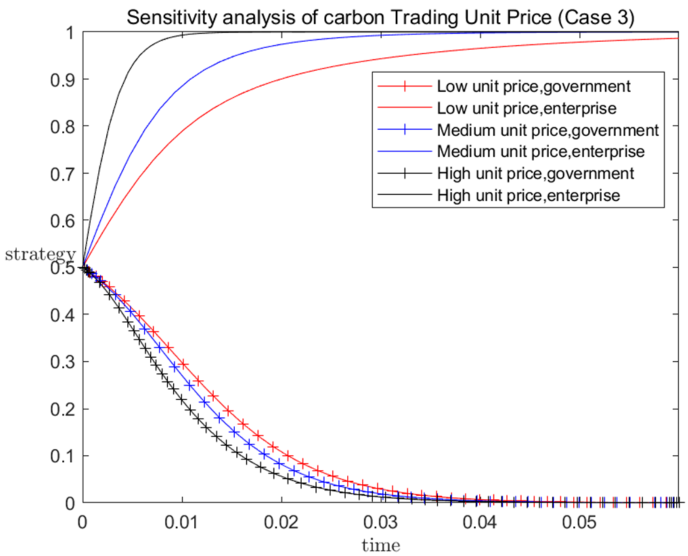


Figure 3. Sensitivity analysis of carbon trading unit price at different levels.

From Figure 3, it can be seen that when the carbon trading unit price is low, it takes a longer time for enterprises to choose the strategy of "using BIM"; and when the carbon trading unit price is high, it takes a shorter time for enterprises to choose the strategy of "using BIM". This is consistent with the expected results.

Under the premise of Case 3, the influence of a single factor, the carbon trading unit price, is considered. It can be deduced that, if other conditions remain unchanged, the greater the difference in carbon tax, the smaller the pay-to-revenue ratio of enterprises, and the shorter the time to realize the evolutionary stability strategy (0,1). Numerical simulation results with Matlab are shown in Figure 4.

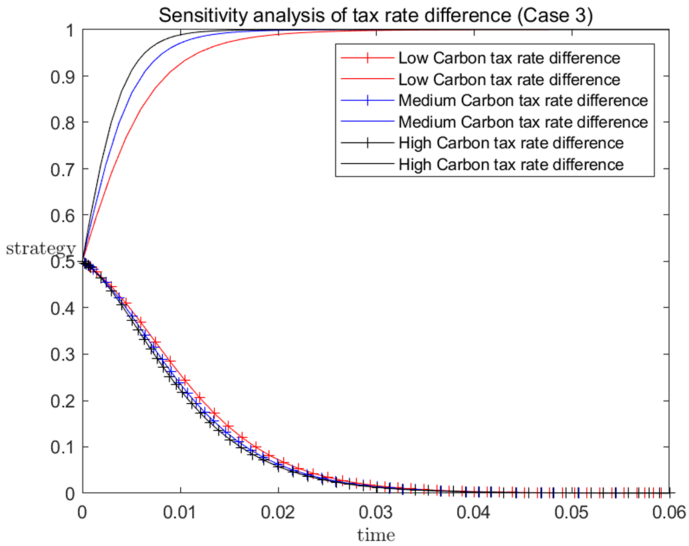


Figure 4. Sensitivity analysis of different carbon tax differences.

As can be seen from Figure 4, other conditions remain unchanged, when the carbon tax difference is small, it takes a long time for the enterprise to choose the strategy of "using BIM technology", while when the carbon tax difference is large, it takes a short time for the enterprise to choose the strategy of "using BIM technology", which is in line with the expected result.

Therefore, increasing the carbon trading unit price and carbon tax difference can effectively shorten the time for enterprises to choose to use BIM technology.

However, carbon trading unit price and carbon tax difference has little influence on the government' choice of the "non-incentive" strategy. Therefore, this paper analyzes the main factors affecting the government's strategy choice in government incentives, that is, discusses the impact of government subsidy level on the timing of the government's strategy choice. It has been shown in the above analysis that when other conditions remain unchanged, the higher the government subsidy coefficient, the higher the government subsidy level. Under different subsidy levels, numerical simulation is carried out with Matlab, and the results are shown in Figure 5.

As shown in Figure 4, when the subsidy level is high, the time required for the government to choose the "non-incentive" strategy is comparatively short, and when the subsidy level is low, the time required for the government to choose the "non-incentive" strategy is comparatively long. The level of government subsidy mainly affects its duration and it should not be too high. Although good incentive effects can be achieved in a short period of time with a high level of government subsidy, there may be an imbalance between the level of government incentives and the ability of enterprise to apply new technology due to the lack of mature time for enterprises to apply new technologies. This may lead to a waste of resources, which is not conducive to the sustainable development of both sides. However, this doesn't mean the government subsidy level should be too low. If the subsidy level is too low, it is unlikely to stimulate the enthusiasm of prefabricated construction enterprises to use BIM. Meanwhile, the time cost of government incentives is too high, which may hinder the development of other projects.

It is unrealistic for the government to give incentives all the time. Over time, the government will eventually choose not to incentivize. In Case 5 and Case 6, the government's strategy choice is 0, while the enterprise's strategy choice is 1 and 0. In both cases, the range of N is the same, but the range of M is different: when $(-M) < 0$, the enterprise policy tends to 1; when $(-M) > 0$, the enterprise policy tends to 0. The paper explores the case where $(-M) = 0$. In this case, there is no evolutionary game stability point (ESS), that is, there is no possibility that all enterprises will eventually use BIM or not use BIM. Therefore, the paper considers the probability that enterprises will eventually use BIM.

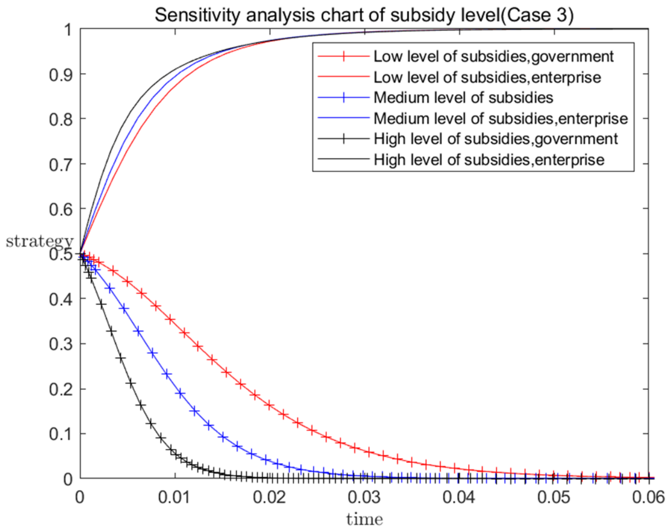


Figure 5. Sensitivity analysis of different levels of government subsidy.

When the cost increment brought to the enterprise by BIM technology is close to the profit, that is, when s = 1 or $M = 0$, the probability that the enterprise chooses to apply BIM will be affected by the initial value. Generally speaking, due to publicity and geographical factors, not all enterprises can enjoy government subsidy, even if it can cover 90% of enterprises. When x = 0.9, the evolution trend of enterprises at different initial proportions is shown in Figure 6.

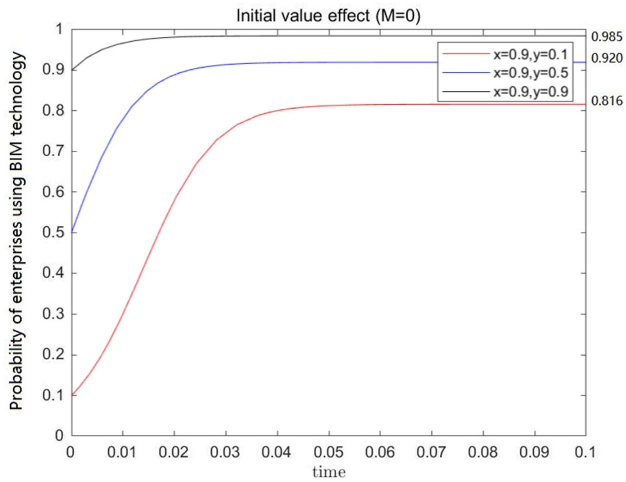


Figure 6. Probabilistic analysis of enterprise choice when x = 0.9.

It can be seen from Figure 6 that when x is 0.9 and y is 0.1, 0.5 and 0.9 respectively, the corresponding probability that enterprises choose to apply BIM is approximately 82%, 92% and 99%. When the government decides to provide large-scale subsidies, no matter what the initial proportion is, more enterprises will eventually choose to apply BIM, and the higher the initial proportion, the stronger the imitation effect. Eventually, the proportion of enterprises that choose to apply BIM technology is also higher.

4.2. Suggestions Based on Numerical Simulation Results

Through the analysis of the level of government subsidy and the payment to income ratio of enterprises, the following suggestions are put forward for the government to formulate policies:

(1) Develop reasonable incentive policies. It is not necessary to pursue the highest level of government subsidy and penalty. As analyzed in the previous section, excessive expenditure and subsidy, even if with low government penalty, will still lead to high government incentive costs and heavy burdens on the government. Besides, if enterprises cannot effectively apply BIM in the short term, there will be an imbalance between government subsidy and enterprise efforts, preventing both sides from benefiting in the long run. However, if the level of subsidy and penalty is too low, the enthusiasm of enterprises to use BIM technology cannot be mobilized, which means government incentives won't have substantial effect. Therefore, the government should evaluate the ability of enterprises to apply BIM when formulating incentive policies. The government should also dynamically adjust the policies according to the real situation, so that the best results of incentive policies can be achieved.

(2) Give full play to the role of environmental regulation. The two environmental regulations: carbon tax and carbon trading, plays a crucial role in promoting the application of BIM by prefabricated construction enterprises. Increase in the unit price of carbon trading and carbon tax rate can reduce the payment to income ratio of prefabricated construction enterprises, which will further promote the application of BIM. Moreover, the government's macro-control of environmental taxes and carbon trading will indirectly prompt the society to pay attention to environmental issues. This can help to create a good atmosphere for green and sustainable development, and form a public opinion orientation, which will bring more social benefits to enterprises to use BIM. Therefore, the government should formulate reasonable taxation and carbon trading policies on the basis of market and enterprise research, and make full use of the market and public opinion to guide the green development of enterprises.

5. Conclusions

By analyzing the entire evolution process of the government and prefabricated construction enterprises and taking into account the main influencing factors such as government subsidy, enterprise payment to income ratio, carbon trading unit price, etc., the following conclusions are drawn:

(1) The incentive intensity and costs of the government, the social benefits and environmental benefits of prefabricated construction enterprises jointly affect the decision-making of both sides. Government incentives play an irreplaceable role in the development stage of prefabricated buildings. Therefore, in addition to the BIM technology incentive costs and administrative costs, the government should also pay attention to the environmental improvement, social progress and government image enhancement brought about by the development of BIM+ prefabricated buildings. In order to achieve the goal of "carbon neutrality and carbon peaking", the government should make full use of the environmental regulation effect, properly control the unit price of carbon trading and carbon tax difference in the market, and promote the development of BIM+ prefabricated buildings.

(2) Whether an enterprise uses BIM is affected by factors such as enterprise income, technology application costs, risk perception, enterprise brand benefits, etc. Therefore, as the main body of the market, enterprises should pay more attention to their cost-effectiveness, focus more on improving their core competitiveness, exert positive influences in competition and cooperation, and establish a good reputation in the industry.

(3) One finding of this paper is that government subsidy can accelerate or delay enterprises' choice to use BIM technology, but has no decisive impact on whether enterprises choose to use BIM technology in the case of ESS. That is to say, in the case of a stable point in an evolutionary game, even if the government makes efforts to

subsidize, enterprises will still give up the strategy of using BIM due to cost increment, risk and other problems, which will only increase the burden on the government. Therefore, the government should avoid giving ineffective subsidies and find ways to promote enterprises' application of BIM from the aspects of environmental and social benefits. This finding will bring enlightenment for the government to formulate reasonable subsidy policy.

(4) In the absence of ESS, that is, when the cost increment brought by BIM technology to the enterprise is close to the profit, the probability that an enterprise ultimately chooses to apply BIM technology is affected by the initial value. The higher the initial value, the higher the probability of the enterprise's final choice to apply BIM technology. When the coverage rate of government subsidies is 90%, the enterprises that initially choose to apply BIM technology account for 10%, 50% and 90% of the total number of enterprises, respectively, and the probability of the overall enterprises applying BIM is 82%, 92% and 99%, respectively. Therefore, the government can promote the initial value of enterprises' applications of BIM technology by increasing publicity and subsidies.

(5) The contributions of this paper are that the research overcomes the limitations of previous studies, analyzes the way that the government promotes the development of prefabricated buildings from the perspective of the application of new technologies, and focuses on the impact of environmental issues under current economy and technology situations. Moreover, the model established in this paper involves more parameters and considers the correlations between each parameter, so that it is more realistic and more adaptable, which provides a good reference for the government to make reasonable policies.

Currently, BIM is widely used in interior decoration and three-dimensional diagram drawing, but in other aspects, especially in solving structural problems such as steel inserting and force analysis, it is not mature enough. This inhibits its development. Therefore, future research may be conducted on the technology improvement of BIM and on the willingness of enterprises to apply of it.

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