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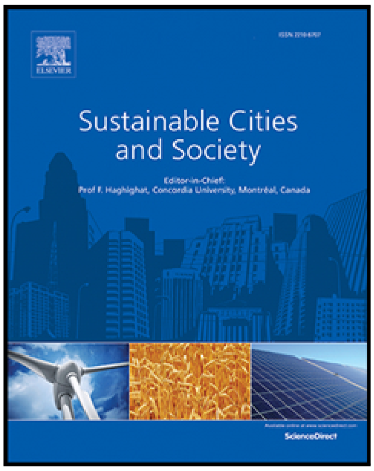

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Highlights

- The decision model simulates the long-term interactions among stakeholders.
- The decision model outputs balance the intertwined interests of stakeholders.
- The case study recommends subsidy to homebuyers with price control.
- The case suggests two moderators: the premium reduction and subsidy proportion.
- The decision model extends the green building movement literature.

Decision Model to Optimize Long-term Subsidy Strategy for Green Building Promotion

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Abstract

Green buildings reduce energy use and CO_2 emissions toward the sustainable built environment. The last milestone of the green building movement is to promote public acceptance, while barriers exist such as the incremental cost for developers and the premium price for homebuyers. Subsidy programs are offered by government agencies to address the barriers; however, most of the subsidy strategies highlight the interest of single stakeholder such as government (policy side), developer (supply side), or homebuyer (demand side). This study creates a decision support model using evolutionary game theory to reach an optimal subsidy strategy among multiple stakeholders and increase the green building acceptance. This model considers the interactions of the government, developer, and homebuyer, and seeks their common interests – the long-term benefits for the society in the contexts of green building movement. Demonstrated via a real residential development project, the model identifies the optimal subsidy strategy and associated factors, e.g., subsidy allocation, subsidy proportion, and premium reduction. The results recommend a subsidy strategy to homebuyers as well as combined with price control. The case study also suggests two moderators on the green building market expansion – the premium reduction and subsidy proportion – which depend on the government's budget and ambitions.

Keywords

Green building movement; decision making; premium pricing; evolutionary game

1. Introduction

According to the International Energy Agency IEA (2019), building construction and operation are responsible for 36% of global energy consumption and 40% of CO_2 emissions. The growth of world population and improvement of living quality continue to challenge the built environment. In this background, the green building (hereinafter GB) movement has emerged globally to improve energy efficiency, health, and comfort in the built environment (Baird et al. 2012; Lin et al. 2016; Zhao et al. 2018). The green building movement started with technological innovations that are energy efficient and environmentally friendly. For example, solar photovoltaic systems reduce water evaporation loss and generate renewable electricity at the same time (Alhejji et al. 2021; Almorox et al. 2021).

The green building movement framework (Zhao et al. 2019) highlights four milestones in the progress toward the green building adoption and acceptance: (1) the establishment of government agencies and regulations, (2) operations of professional organizations and industry standards, (3) promotion of public policy, and (4) influence on public behavior. The advances in green building technology reflect that public behavior is currently the essential barrier to green building adoption. The green building movement framework specifies two types of public behaviors, i.e., developer behavior and homebuyer behavior. From the developer's perspective, green buildings require higher development costs and should have a premium price as viewing energy efficiency to be an extra value for profit (Darko and Chan 2017; Hwang and Tan 2012; Kats 2003; Yudelson 2010). For example, the literature has found that green building projects cost 1–12.5% more for development (Portnov et al. 2018) and 3.1–9.4% more for the green building certification (Uğur and Leblebici 2018). From the homebuyer's perspective, green buildings have a higher price and they are willing to pay the premium only when they can obtain a greater benefit (Kahn and Kok 2014; Ofek and Portnov 2020). For example, the average transaction price of a certified green building is found to be 6.9% higher in the Chinese real estate market (Zhang et al. 2017).

A dilemma has emerged to reach the last milestone in the green building movement, particularly about the public acceptance. On one hand, developers prefer green building projects only if a premium price is expected to cover the extra design and construction costs and bring additional profits (Kats 2003). On the other hand, homebuyers prefer green buildings but hesitate to pay the premium (Federico and Marta 2021). In practice, developers pass 10–31% of the extra development costs for green buildings to homebuyers to obtain a higher profit (Portnov et al. 2018). In other words, developers will not adopt green building technology in their projects if homebuyers are not willing to pay the premium price. Often, both developers and homebuyers intend not to change their behaviors due to psychological routines. In this context, GB subsidy programs become a critical government policy used in many countries to promote the public acceptance of green buildings (Olubunmi et al. 2016; Wang et al. 2021; Zou et al. 2017).

A green building subsidy, i.e., government incentives, is a form of financial aid with the goal to promote the adoption of green building technologies and the acceptance of green buildings in the market. The subsidy can be extended to a developer, e.g., in China (Kong and He

2021), or a homebuyer, e.g., in Israel (Cohen et al. 2019). The subsidy strategy for developers includes monetary reimbursement, tax deduction, and floor area ratio benefits (Diyana and Abidin 2013; Olubunmi et al. 2016; Zou et al. 2017). The subsidy strategy for homebuyers includes monetary rebates, high mortgage lines, low mortgage rates, and tax deductions (Li et al. 2014). However, there is a lack of agreement and evidence showing what subsidy strategy could promote the public acceptance of green buildings and maximize societal benefits.

The game theory allows players to make decisions simultaneously on the basis of guaranteeing their corresponding payoff (Romanuke 2021), and it is widely applied to solve the sustainability issues in the supply chain. For example, (Giri and Dey 2020) established two game models to devise the optimal pricing strategies of supply chain members. The results show that ex-ante pricing commitment is beneficial for the whole supply chain as well as the supply chain entities. (Samanta and Giri 2021) established a two-echelon supply chain model to analyze the optimal decisions between the vendors and the buyers to bear warranty costs. The results show that the buyer agrees to bear a portion of the warranty cost is a better decision. The game theory has been used in the building literature to examine the GB construction process (Feng et al. 2020), carbon tax policy (Qiang et al. 2021), GB technology adoption (Chen et al. 2021; Yang et al. 2021), and even GB incentives (Fan and Hui 2020; Fan and Wu ; Liu et al. 2022). For example, Chen et al. (2021); Yang et al. (2021) found that government incentives are essential to GB technology adoption and financial subsidies improve stakeholders' motivations.

However, these studies about GB subsidy are focused on the perspective of single stakeholder such as the supply side. A critical factor that hinders the GB adoption is often ignored: the excessive premium transferred to homebuyers (Hu et al. 2014). Thus, homebuyers should be an important stakeholder in the GB adoption. Recently, Qian et al. (2022) included homebuyers in the game model and found that government subsidies improve consumers' enthusiasm for GB purchases. Qiao et al. (2022) demonstrated that strong incentives and punishment could drive strong local government guidance in the GB development. However, these models simplify the subsidy strategy (e.g., only financial compensation) and fail to consider the constraints of the subsidy budget. In addition, the traditional game theory used in the aforementioned studies is limited due to the assumption of complete rationality. To address the gaps, our model is built upon the evolutionary game theory that contracts the bounded rationality where players do not have the best strategy at the beginning and improve their decisions by continuous learning and imitations. The model allows for simultaneous stimulation of multiple stakeholders and their interactions rather than a single player.

The objective of this study is to create a decision model that can produce the optimal subsidy strategy for the common interest of key stakeholders, i.e., government, developer, and homebuyer. Specifically, this study attempts to address the following research questions: (1) what subsidy strategy can maximize the long-term benefit among stakeholders in the green building market? (2) what are the interactions among government, developers, and homebuyers in the design, build, and sales of green buildings? Answering the research questions helps extend the green building movement literature by connecting the public policy in the political realm with the public behavior in civil society. Especially, the interests of stakeholders are different and even conflicting: (1) government agencies seek environmental benefit and social credibility but have a limited budget to offer subsidy (Chen et al. 2021); (2) developers seek profits but need to invest a higher development cost (Hu et al. 2014); and (3) homebuyers seek low energy expenditure and better living quality but have a limited willingness to pay (Heerwagen 2000; Kats 2003). The outputs seek a joint, balanced benefit across the three players and imply for policymakers how to effectively implement a green building subsidy program in the long run (Menassa and Baer 2014).

2. Model Development

The evolutionary game theory emphasizes a simultaneous process to reach the equilibrium of the whole system. The concept of evolutionary, stable strategy considers players to play multiple games and dynamically adjust their strategies (Smith and Price 1973). In this study, we use the evolutionary game theory to create a mathematical decision model to optimize the GB subsidy strategy among the government, developer, and homebuyer. The flowchart of the model development is shown in Figure 1.

<<**Figure 1.** The flowchart of the decision model development >>

2.1. Model setup - Players and decisions

Our model includes three players: government agencies, developers, and homebuyers. We assume they are limited rational economic parties. That is, their strategies cannot reach equilibrium at the beginning of the game and could reach an optimal strategy profile to fit the interest of all parties through a process of continuous learning and correction.

Figure 2 displays the decision structure for each of the three players: (1) government agencies have two choices to offer GB subsidy (G_1 with a probability = x) or not offer (N_1 with a probability = 1–x); (2) developers have two choices to build either GB projects (G_2 with a probability = y) or non-GB projects (N_2 with a probability = 1–y); and (3) homebuyers have two choices to purchase either GB homes (G_3 with a probability = z) or non-GB homes (N_3 with a probability = 1–z).

<<**Figure 2**. Structure of players and decisions in the evolutionary game>>

2.2 Model setup - Variables and payoff matrix

Many factors affect the public acceptance of green buildings such as economic level, social benefits, and cultural differences. Most of them are uncertain or cannot be quantified; therefore, key variables are selected for numerical simulation in this paper. Table 1 lists the variables used in the evolutionary game. Table 2 represents the payoff matrix for each of the six subsidy strategies based on the model setup for players and decisions. The payoff mechanisms are explained as follows.

- A green building subsidy by a government agency can compensate for the incremental cost at $\alpha\Delta C$ ($\alpha >= 0$) for a developer when switching the choice of non-GB to GB. The subsidy can also compensate the premium price at $\beta\Delta R$ ($\beta >= 0$) for a homebuyer when switching the choice of non-GB to GB.
- A homebuyer can gain the extra benefit at $\gamma\Delta U$, based on the level of awareness about GB benefits, e.g., better thermal comfort, productivity, and health (Heerwagen 2000; Kats 2003). The literature has identified that the awareness level affects the GB demand (He et al. 2022). That is, a strong γ (i.e., more a homebuyer understands GB benefits) increases the willingness to pay for GB (Ofek and Portnov 2020).
- In case homebuyers choose to purchase GB and developers choose not to build GB, they will pursue other developers who meet their demand.

<<**Table 1.** List of Variables in the Game>>

<<**Table 2.** Payoff Matrix for the Players>>

2.3 Model setup - Replicator dynamics

The expected benefits and replicator dynamics for green building promotion for each player decision are explained as follows:

Let B_{11} be the benefit when government agencies choose to offer GB subsidy (decision G_1):

$$B_{11} = yz(kR_1 - \beta\Delta R) - y(kR_2 + \alpha\Delta C + T) + kR_2 + S + T$$

Let B_{12} be the benefit when government agencies choose to not offer GB subsidy (decision N_1):

$$B_{12} = yzk(R_1 + R_2) - ykR_2 - zkR_2 + kR_2$$

Then, the replicator dynamics equation for government agencies is:

$$F(x) = \frac{dx}{dt} = x(1-x)(B_{11} - B_{12}) = x(1-x)[S + T - yz\beta\Delta R - y(\alpha\Delta C + T)]$$

(1) Let B_{21} be the benefit when developers choose to develop GB project (decision G_2):

$B_{21} = x\alpha\Delta C + z(1-k)R_1 - C_1$

Let B_{22} be the benefit when developers choose to develop non-GB project (decision N_2):

$B_{22} = -xT + (1-z)(1-k)R_2 - C_2$

Then, the replicator dynamics equation for developer is:

$F(y) = \frac{dy}{dt} = y(1-y)(B_{21} - B_{22}) = y(1-y)[x(\alpha\Delta C + T) + z(1-k)(R_1 + R_2) - (1-k)R_2 - \Delta C]$

(2) Let B_{31} be the benefit when homebuyers choose to purchase GB home (decision G_3):

$$B_{31} = x\beta\Delta R + U_2 + \gamma\Delta U - R_1$$

(3) Let B_{32} be the benefit when homebuyers choose to purchase non-GB home (decision N_3):

$$B_{32} = U_2 - R_2$$

Then, the replicator dynamics equation for homebuyer is:

$F(z) = \frac{dz}{dt} = z(1-z)(B_{31} - B_{32}) = z(1-z)(x\beta\Delta R + \gamma\Delta U - \Delta R)$

2.4 Stability analysis for government

The first derivative of government's replicator dynamics is:

$$F(x)' = \frac{\partial F(x)}{x} = (1-2x)[S + T - yz\beta\Delta R - y(\alpha\Delta C + T)]$$

Let $F(x) = 0$ and we found three solutions: $x^* = 0$, $x^* = 1$ and $y^* = \frac{S+T}{z\beta\Delta R + \alpha\Delta C + T}$ (although y^* is not a certain number). Accordingly, we discuss the three solutions as follows:

(1) if $y \equiv y^* = \frac{S+T}{z\beta\Delta R + \alpha\Delta C + T}$, $F(x) \equiv 0$, then regardless of variable values, x is constant over time, indicating that the decision of G_1 or N_1 is not stable for government.

(2) if $0 < y < \frac{S+T}{z\beta\Delta R + \alpha\Delta C + T}$, let $F(x) = 0$, solve that $x^* = 0$, $x^* = 1$, then $F(0)' > 0$ and $F(1)' < 0$. According to the principle of stability of replicator dynamics, this strategy is stable only when $F(x)' < 0$. Thus, $x^* = 1$ is a stable point, indicating that government will eventually choose the decision G_1 – "offering GB subsidy" (see Figure 3a).

(3) if $\frac{S+T}{z\beta\Delta R + \alpha\Delta C + T} < y < 1$, let $F(x) = 0$, solve that $x^* = 0$, $x^* = 1$, then $F(0)' < 0$ and $F(1)' > 0$. Thus, $x^* = 0$ is a stable point, indicating that government will eventually choose the decision N_1 – "not offering GB subsidy" (see Figure 3b).

<<**Figure 3**. The evolutionary trajectory of government strategy>>

The stability analysis suggests that government offer GB subsidy and keep the budget within a reasonable range. First, the societal benefits harvested by government are assumed to be greater than the total subsidy spent: $S > \alpha \Delta C + \beta \Delta R$ and then $\frac{S+T}{z\beta \Delta R+\alpha \Delta C+T} > 1$, which indicates that the evolutionary game should always evolve to offer GB subsidy. Second, given a huge subsidy budget, the subsidy spent is possible to be greater than the societal benefits: $S < \alpha \Delta C + \beta \Delta R$. In this case, the evolutionary game should evolve to not offer GB subsidy.

2.5 Stability analysis for developer

The first derivative of developer's replicator dynamics is:

$$F(y)' = \frac{\partial F(y)}{y} = (1-2y)[x(\alpha \Delta C + T) + z(1-k)(R_1 + R_2) - (1-k)R_2 - \Delta C]$$

Let $F(y) = 0$ and three solutions are found: $y^* = 0$, $y^* = 1$, and $x^* = \frac{\Delta C+(1-k)R_2-z(1-k)(R_1+R_2)}{\alpha \Delta C+T}$. Accordingly, we discuss the three solutions as follows:

(1) if $x \equiv x^* = \frac{\Delta C+(1-k)R_2-z(1-k)(R_1+R_2)}{\alpha \Delta C+T}$, $F(y) \equiv 0$, then y will not change over time, indicating that developing GB or non-GB project is not stable for developer.

(2) if $0 < x < \frac{\Delta C+(1-k)R_2-z(1-k)(R_1+R_2)}{\alpha \Delta C+T}$, let $F(y) = 0$, solve that $y^* = 0$ and $y^* = 1$, then $F(0)' < 0$ and $F(1)' > 0$. Thus, $y^* = 0$ is a stable point, indicating that developers will eventually choose the decision G_2 – "developing GB project" (see Figure 4a).

(3) if $\frac{\Delta C+(1-k)R_2-z(1-k)(R_1+R_2)}{\alpha \Delta C+T} < x < 1$, let $F(y) = 0$, solve that $y^* = 0$, $y^* = 1$, then $F(0)' > 0$ and $F(1)' < 0$. Thus, $y^* = 1$ is the stable point, indicating that developer

will eventually choose the decision N_2 – “developing non-GB project” (see Figure 4b).

<<**Figure 4**. The evolutionary trajectory of developer strategy>>

The stability analysis suggests multiple findings to promote GB development. First, the high participation of government and homebuyer increases the likelihood for developers to build GB projects. Second, the simultaneous use of subsidies and penalties is effective to increase the likelihood for developers to build GB projects. Third, a higher premium price also increases the likelihood for developers to build GB projects, although this may increase homebuyer’s financial burden.

2.6 Stability analysis for homebuyer

The first derivative of homebuyer’s replicator dynamics is:

$$F(z)' = \frac{\partial F(z)}{z} = (1-2z)(x\beta\Delta R + \gamma\Delta U - \Delta R)$$

Let $F(z) = 0$ and three solutions are found: $z^* = 0$, $z^* = 1$, and $x^* = \frac{\Delta R - \gamma\Delta U}{\beta\Delta R}$. Accordingly, we discuss the three scenarios as follows:

(1) if $x \equiv x^* = \frac{\Delta R - \gamma\Delta U}{\beta\Delta R}$, $F(z) \equiv 0$, then z is constant over time, indicating that purchasing GB or non-GB home is not stable for homebuyer.

(2) if $0 < x < \frac{\Delta R - \gamma\Delta U}{\beta\Delta R}$, let $F(z) = 0$, solve that $z^* = 0$ and $z^* = 1$, then $F(0)' < 0$ and $F(1)' > 0$. Thus, $z^* = 0$ is a stable point, indicating that homebuyers will eventually choose the decision G_3 – “purchasing GB home” (see Figure 5a).

(3) if $\frac{\Delta R - \gamma\Delta U}{\beta\Delta R} < x < 1$, let $F(z) = 0$, solve that $z^* = 0$, $z^* = 1$, then $F(0)' > 0$ and

$F(1)' < 0$. Thus, $z^* = 1$ is the stable point, indicating that homebuyers will eventually choose the decision N_3 – "purchasing non-GB home" (see Figure 5b).

<<**Figure 5.** The evolutionary trajectory of homebuyer strategy>>

The stability analysis suggests multiple findings to promote GB sales. First, homebuyers are more likely to purchase GB when they see a greater benefit than the premium price. Second, the subsidy helps offset the premium and is effective to increase the likelihood for homebuyers to choose GB, although the premium borne by homebuyers may cause a problem in the long run. Third, a stronger awareness of GB benefits can increase the willingness to pay and stimulate homebuyers to purchase GB.

3. Model Demonstration and Case Study

We applied our decision model to a real-world project to identify the optimal subsidy strategy to promote green buildings in the long term. The case demonstrated how to use our decision model to find the subsidy strategy for developers (i.e., α, the proportion of increment cost covered by subsidy) and homebuyers (i.e., β, the proportion of premium price covered by subsidy). The case project is a residential community located in Tianjin city, China (Figure 6). The project is jointly developed by China and Singapore, which is a demonstration project of green buildings and sustainability. The project has been certified as "3-star" in the China Green Building Label which is the national standard for rating GB performance in life-cycle energy, land, water, and material savings. The rating system classifies green buildings into three levels: 1-star, 2-star, and 3-star, where 3-star GB indicates the highest performance. Seven indicators are considered in the GB evaluation: (1) land saving and outdoor environment, (2) energy saving and utilization; (3) water saving and utilization, (4) material resource utilization, (5) indoor environmental quality, (6) construction management, and (7) operation management (Ding et al. 2018).

<< **Figure 6.** The case project >>

In this case, the initial probabilities of the three players (i.e., *x*, *y*, and *z*) were set as follows: (1) $x = 0.8$, considering the Chinese government has a strong administrative role in regulating the housing market (Harrington and Hsu 2018); (2) $y = 0.7$, considering new green building area should account for 70% in Chinese cities and towns by 2022; and (3) $z=0.5$, considering the similar assumptions and setups used in the methodology of previous studies (Du et al. 2020; Qiang et al. 2021). The variable values were listed in Table 3. For easy calculation, the base unit of price is 10^2 CNY/m^2. The simulations were performed in MATLAB 2018a.

<<**Table 3.** List of Variable Values and Explanations in Case Study >>

3.1 Strategy 1: Subsidy to developers

In this strategy, government subsidy is used to compensate developers (Vyas and Jha 2018). The simulation demonstrates how this strategy influences the choices of developers and homebuyers under various subsidy proportions (α). The results (Figure 7a) show that developers would eventually "build non-GB" (y = 0) and homebuyers would then "purchase non-GB" (z = 0), regardless of the subsidy proportion (α from 0.16 to 1.16). It is noteworthy that the choices of developers (build non-GB) and homebuyers (purchase non-GB) do not change even if the subsidy can completely cover the incremental cost for developers (α >= 1.0). The results (Figure 7b) show that the relationships of decisions among the three players do not change, suggesting the incremental cost is not a major obstacle to GB adoption (Hoffman 2008; Nguyen et al. 2017). Given the existence of government subsidy (i.e., x approaching 1.0), developers are likely to "build non-GB" and homebuyers are likely to "purchase non-GB", and the likelihoods increase more sharply when the subsidy proportion decreases. Overall, findings indicate that this strategy is not effective in the long term.

<<**Figure 7.** Decision evaluation of government (x), developer (y), and homebuyer (z) when green building subsidy is only provided to developers. >>

3.2 Strategy 2: Subsidy to homebuyers

In this strategy, government subsidy is used to compensate homebuyers (Vyas and Jha 2018). The results (Figure 8a) show that developers change their decision to eventually "build GB" (y = 1) and homebuyers also change their decision to "purchase GB" (z = 1) when subsidy covers more than 12.5% of the premium for homebuyers (β >= 0.125, 1.25×10^2 CNY/m^2 in this case). The results (Figure 8c) show that developers are likely to "build GB" and homebuyers are likely to "purchase GB" given a considerable subsidy proportion (β >= 0.125), and vice versa. The results (Figure 8b) show an unsolvable situation when subsidy proportion increases to be higher than 19%, for example, 25%, suggesting that a very strong homebuyer subsidy can reduce the willingness to buy GB (Portnov et al. 2018). This indicates that subsidy to homebuyers only functions in a certain range ($0.125 < \beta < 0.19$ in this case). Overall, findings indicate that this strategy (homebuyers) is effective in the long term. The subsidy must be equivalent to 12.5%–19% of the premium (1.25–1.9 $\times 10^2$ CNY/m^2 in this case) and a higher subsidy proportion can accelerate GB acceptance in the market (faster).

<<**Figure 8.** Decision evaluation of government (*x*), developer (*y*), and homebuyer (*z*) when green building subsidy is only provided to homebuyers. >>

3.3 Strategy 3: Price control with no subsidy

In this strategy, government agencies use administrative measures, rather than incentive measures, to control GB sale price and ensure the premium (also developer profit) is within a reasonable range. The simulation demonstrates how this strategy influences the choices of developers and homebuyers under various premium reductions. The results (Figure 9) show that developers change their decision to eventually "build GB" ($y = 1$) when the premium reduces by 12.5% or more (1.25×10^2 CNY/m^2 in this case) and homebuyers change their decision to "purchase GB" ($z = 1$) when the premium reduces by 15% or more (1.5×10^2 CNY/m^2 in this case). Although a reduced premium lowers the developer's profit, the premium (ΔR=10×10^2

CNY/m^2) is greater than the incremental cost (ΔC=5×10^2 CNY/m^2). In other words, developers are profitable to build GB projects when $\Delta R > \Delta C$. Overall, findings indicate that this strategy (price control) is effective in the long term. The price reduction should be in the range of 15%–50% of the premium (1.5–5.0 ×10^2 CNY/m^2 in this case).

<<**Figure 9.** Decision evaluation of developer (y) and homebuyer (z) under price control>>

3.4 Strategy 4: Subsidy to developers combined with price control

In this strategy, government agencies provide subsidy to developers and control GB price. The results (Figures 10a and 10b) show that, when the premium reduces by less than 12.5%, developers eventually "build non-GB" (y = 0) and then homebuyers eventually "purchase non-GB" (z = 0), regardless of the subsidy proportion. The results (Figure 10c) show that when the premium reduces by 12.5% or more, developers eventually "build GB" (y = 1), regardless of the subsidy proportion. The results (Figure 10d) show that when the premium reduces by 15% or more, developers eventually "build GB" (y = 1) and homebuyers "purchase GB" (z = 1), regardless of the subsidy proportion. Noteworthy is that given a strong initial subsidy (α >= 0.56), government can eventually "not offer subsidy" (x = 0). Overall, findings indicate that this strategy is effective in the long term when the premium is reduced by at least 15%. The findings are consistent with strategy 3 but with the help of subsidy the game equilibrium can be achieved faster.

<< **Figure 10.** Decision evaluation of government (x), developer (y), and homebuyer (z) when subsidy is provided to developers and premium is reduced. >>

3.5 Strategy 5: Subsidy to homebuyers combined with price control

In this strategy, government agencies provide subsidy to homebuyers and control GB price. The results (Figure 11a-11c) show that, when the premium reduces less by 12.5%, the subsidy can moderate both developers and homebuyers to eventually “build GB” (y = 1) and “purchase GB” (z = 1). The required subsidy proportion is reliant on the premium reduction. That is, a larger amount of premium reduction would require a smaller subsidy proportion to change the choices of developers and homebuyers. The results (Figure 11d) show that, when the premium reduces by more than 12.5%, developers eventually “build GB” (y = 1) and homebuyers “purchase GB” (z = 1), regardless of the subsidy proportion. Here, the subsidy proportion moderates the speed to reach equilibrium. Overall, findings indicate that this strategy is effective in the long term. The premium reduction can save the subsidy and accelerate green building acceptance in the market.

<<**Figure 11.** Decision evaluation of government (x), developer (y), and homebuyer (z) when subsidy is provided to homebuyer and premium is reduced.>>

3.6 Summary

Five strategies are analyzed using our decision model. The results show that four out of the five strategies are effective in the long term under various conditions. The administrative measures on GB price control can be a great supplement to the subsidy policies; however, a great social cost might have to be paid by government to implement administrative measures to intervene in the market. Overall, the premium reduction and subsidy proportion are two moderators to determine how fast the equilibrium can be obtained. Back to this case project, our decision model recommends strategy 5 (subsidy to homebuyers combined with price control) to be the optimal solution and provides an effective range of variables, for example, subsidy proportion. The final subsidy specifics are depending on government's budget (how much they can offer) and ambitions (how fast they envision the change).

4. Discussion

4.1 Subsidy allocation between developer and homebuyer

The green building movement needs the buy-in from developers (i.e., supply side) and homebuyers (i.e., demand side). Both sides suffer from the high cost to build GB or purchasing GB (McCoy et al. 2018; Zhao et al. 2016). Government subsidy has been used in many countries and regions to offset the high costs. Our model confirms that "offering subsidy" should be an effective strategy in the long run. Moreover, our decision model identifies the optimal trade-off showing how to allocate subsidies between the supply side and demand side. Based on the simulation in the case demonstration, subsidy to the demand side (homebuyers) seems more effective than the supply side (developers) to increase green building market acceptance in the long term. In other words, the market demand plays a more important role in the continuous growth of green buildings. As explained by Carter (2006), the growth in customer demand encourages developers to apply sustainable features to building projects. The GB markets in many countries and regions are driven by government and lack sufficient demands, which is normal based on the procedure of the green building movement. The next step to further promote the GB markets is the key: how to effectively foster public acceptance. Thus, our findings highlight a new strategy that is focused on homebuyers, namely the demand side.

4.2 A reasonable premium

A premium is the extra cost that consumers are willing to pay for additional quality to regular products. By paying for the premium, homebuyers can enjoy energy efficiency, indoor air quality, and quality of life that are rooted in the feature of green buildings. The premium is always a reward for developers to apply energy-efficient technologies, materials, and equipment in construction projects. However, the premium is way too high in the current market that can be triple the incremental development cost. The excessive premium transferred to homebuyers, compared to the incremental development cost, becomes a key factor to hinder green building acceptance. Our decision model allows identifying the reasonable range of premium that ensures a long-term healthy market. The reasonable premium can lead to long-term green building growth and can also catalyze the impact of subsidy and accelerate rapid growth of green buildings in the market. The premium reduction can be reached by administrative measures from government or market behaviors from developers. The market expansion and fast delivery could marginalize the incremental development costs (Rehm and Ade 2013). In other words, a lower premium allows developers to win a bigger market and retain profit.

4.3 A long-term game of three players

Our model is built upon the evolutionary iterations that reflect the long-term interactions among three players: government, developer, and homebuyer. Our results show that GB development is driven by internal demand. In other words, the behaviors of developers depend on the motivation of homebuyers. Our game model is different from other studies that only consider players on the supply side (Cao et al. 2022). These studies emphasize the importance of developers and contractors while overlooking their interactions with consumers in a complex system. In other words, these studies only consider the short-term subsidy effect at the public policy incentive stage. In contrast, the case study in our demonstration shows that the subsidy on developers helps increase the GB market in the early stage for a short period but the GB market would then decline. That is, the demand-driven GB operation mode is sustainable. In addition, our model considers the freedom of homebuyers to choose GB or not, which is different from Feng et al. (2020) that assumes the passive GB acceptance by homebuyers.

4.4 Limitations and future scope

The study has limitations and informs future studies. First, some variables in our decision model have difficulty to quantify the initial value. For example, we had to set the initial value of homebuyers who prefer GB to 0.5 based on existing studies. Noteworthy is that the exact percentage of homebuyers willing to purchase GB is often unclear. In response, future studies may use surveys as an alternative data collection means to fill the initial variable values in their specific cases. Second, a case project is used to demonstrate the application of our decision model and the findings from the numerical simulation process fit the case and might not avoid the particularity of the project contexts. Future studies may include more case studies to verify the model reliability.

5. Conclusion

This study fills the gap of decision support models to reach the optimal subsidy strategy among multiple stakeholder (players) to increase green building acceptance. Unlike previous models that stress the interest of the government (policy side), developers (supply side), or homebuyers (demand side), our model wraps them to reach the common interest of the three stakeholders – the long-term benefits for the society in the contexts of green building movement. Owing to the evolutionary game theory that seeks a stable equilibrium for all players, our model is novel to consider the interactions among the three key stakeholders in designing the GB subsidy policy. The decision model outputs the optimal subsidy strategy with associated factors (e.g., subsidy allocation, subsidy proportion, and premium reduction). A real-world case study demonstrates the application of our decision model. The case study elucidates that the combined strategy of homebuyer subsidy and price control can improve the long-term growth of green buildings. Findings from the case suggest that premium reduction and subsidy proportion moderate the market expansion speed. The specifics of the two moderators are determined by the government's budget (how much they offer) and ambitions (how fast they envision the change). Overall, the model provides policymakers a decision tool to obtain the long-term GB subsidy policy in an attempt to promote green buildings.

Acknowledgment

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Declaration of Competing Interest

None.

Appendix: MATLAB code

```
%Create a script function
%Define a differential function
function dxdt=differential(t,x)
    dxdt=[x(1)*(1-x(1))*(S+T-β*ΔR*x(2)*x(3)-(α*ΔC+T)*x(2));x(2)*(1-x(2))*((1-k)*(R1+R2)*x(3)+(α*ΔC+T)*x(1)-(1-k)*R2-ΔC);x(3)*(1-x(3))*(β*ΔR*x(1)+γ*ΔU-ΔR)];%Manually assign corresponding values to parameters
end

%Enter the command window
%Flat graphics
for i=0.8
  for j=0.7
    for m=0.5
    [T,Y]=ode45('differential',[0 T],[i j m]);%Evolution time is set by yourself

    figure(1)
    grid on
    plot(T,Y(:,1),'-','lineWidth',2.3,'color',[1,0.4,0.3]);
    hold on
    plot(T,Y(:,2),'-','lineWidth',2.3,'color',[0.26,0.43,0.9]);
    hold on
    plot(T,Y(:,3),'-','lineWidth',2.3,'color',[0.12,0.56,0.1]);
    hold on
    end
  end
end
xlabel('\fontsize{17}\fontname{Times New Roman}Evolution time t','FontWeight','bold')
ylabel('\fontsize{17}\fontname{Times New Roman}Strategy choice probability','FontWeight','bold')
set(gcf,'color',[1,1,1])
set(gca,'FontName','Times New Roman')
set(gca,'YLim',[0 1]);%Data range of the Y axis
set(gca,'YTick',[0:0.1:1]);%Coordinate scale
set(gca,'YTickLabel',[0:0.1:1]);%Tick labels
set(gca,'FontName','Times New Roman','FontSize',17);%Axis font size
set(gca,'looseInset',[0 0 0 0],'linewidth',2)%Coordinate line segment
```

```
grid off

%Three-dimensional graphics
for i=0.8
  for j=0.7
    for m=0.5
    [T,Y]=ode45('differential',[0 T],[i j m]);%Evolution time is set by yourself

    figure(2)
    plot3(Y(:,1),Y(:,2),Y(:,3),'-o','linewidth',2,'color',[0.55,0.5,0.48]);
    xlabel('\fontsize{13.2}\fontname{Times New Roman}Governments x','FontWeight','bold')
    ylabel('\fontsize{13.2}\fontname{Times New Roman}Developers y','FontWeight','bold')
    zlabel('\fontsize{13.2}\fontname{Times New Roman}Homebuyers z','FontWeight','bold')
    grid on
    hold on
    end
  end
end
set(gca,'XTick',[0:0.1:1]);%Coordinate scale of the X axis
set(gca,'YTick',[0:0.1:1]);%Coordinate scale of the Y axis
set(gca,'ZTick',[0:0.1:0.5]);%Coordinate scale of the Z axis
set(gca,'FontName','Times New Roman','FontSize',17);
stem3(Y(:,1),Y(:,2),Y(:,3),'color',[0.55,0.5,0.48])
set(gcf,'color',[1,1,1])
```

Journal Pre-proof

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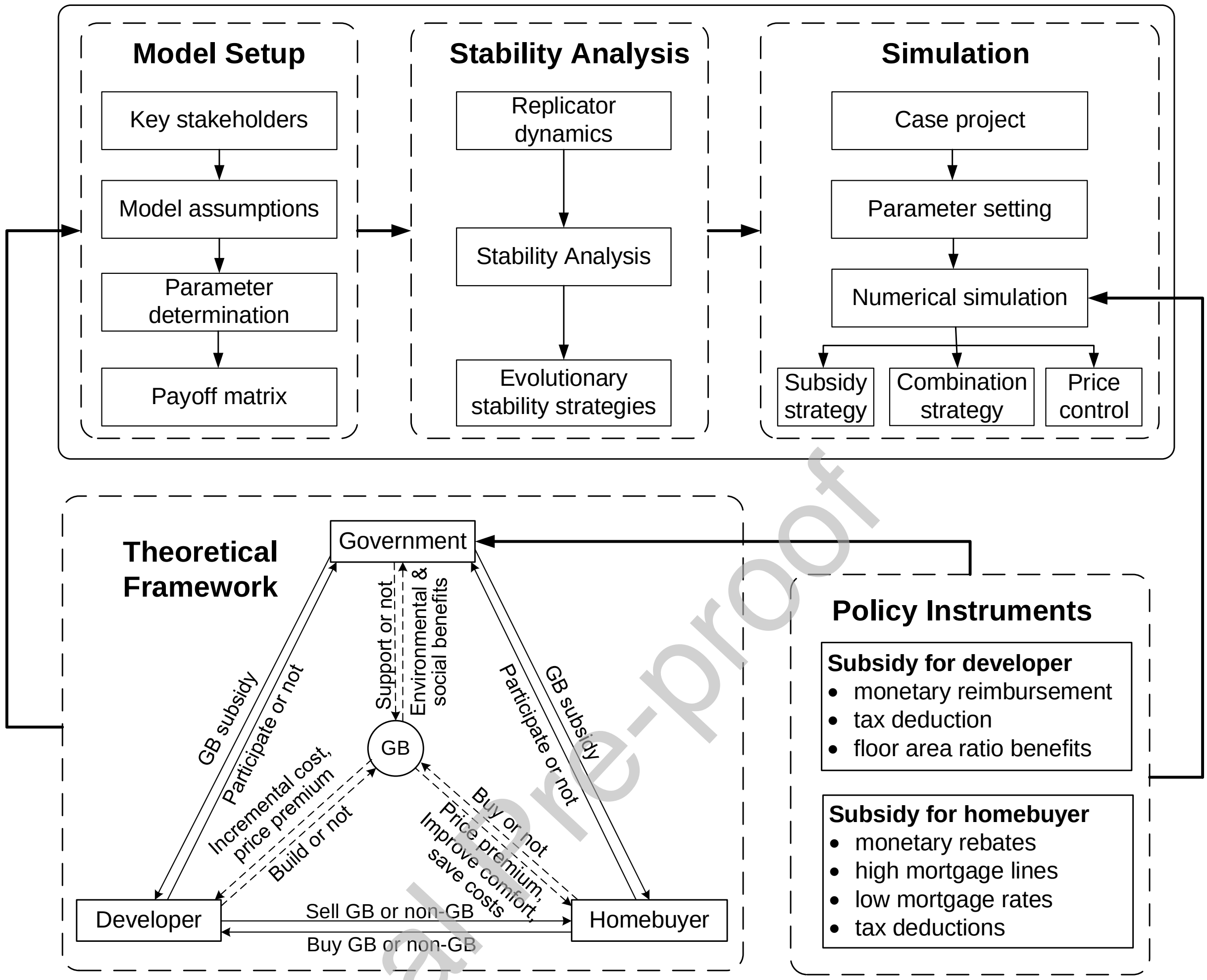


Figure 1. The flowchart of the decision model development

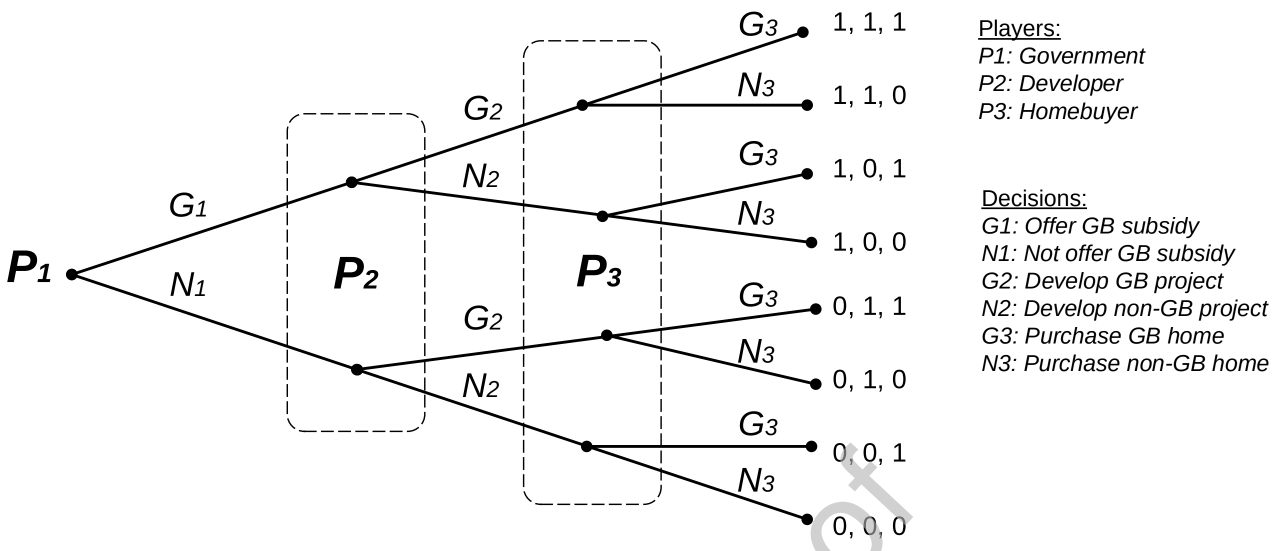


Figure 2. Structure of players and decisions in the evolutionary game

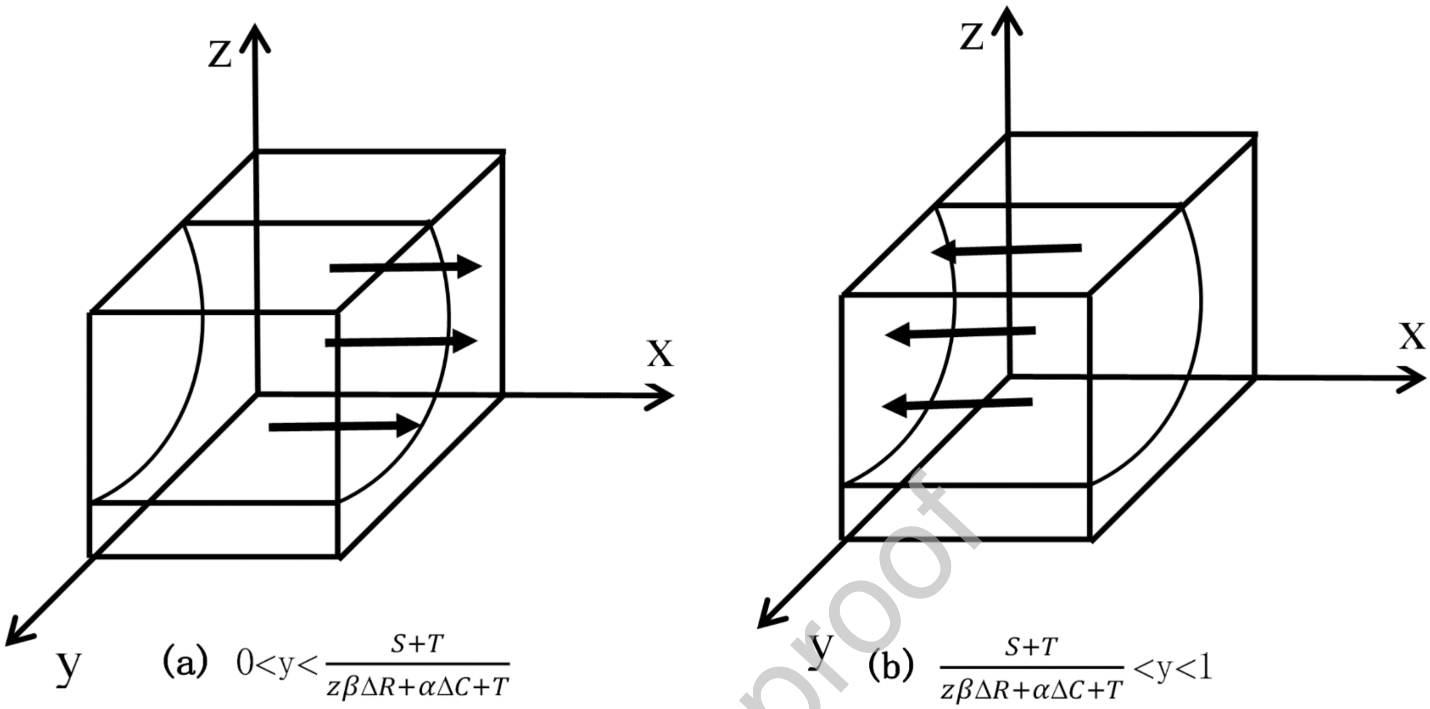


Figure 3. The evolutionary trajectory of government strategy

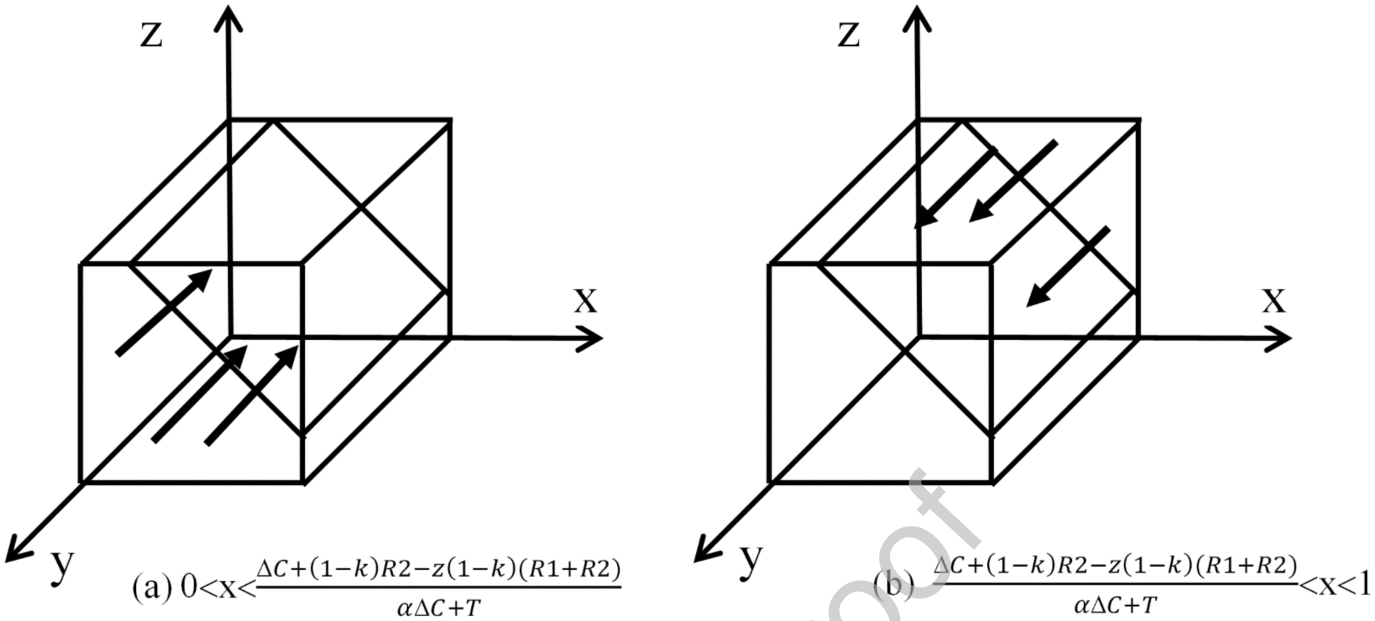


Figure 4. The evolutionary trajectory of developer strategy

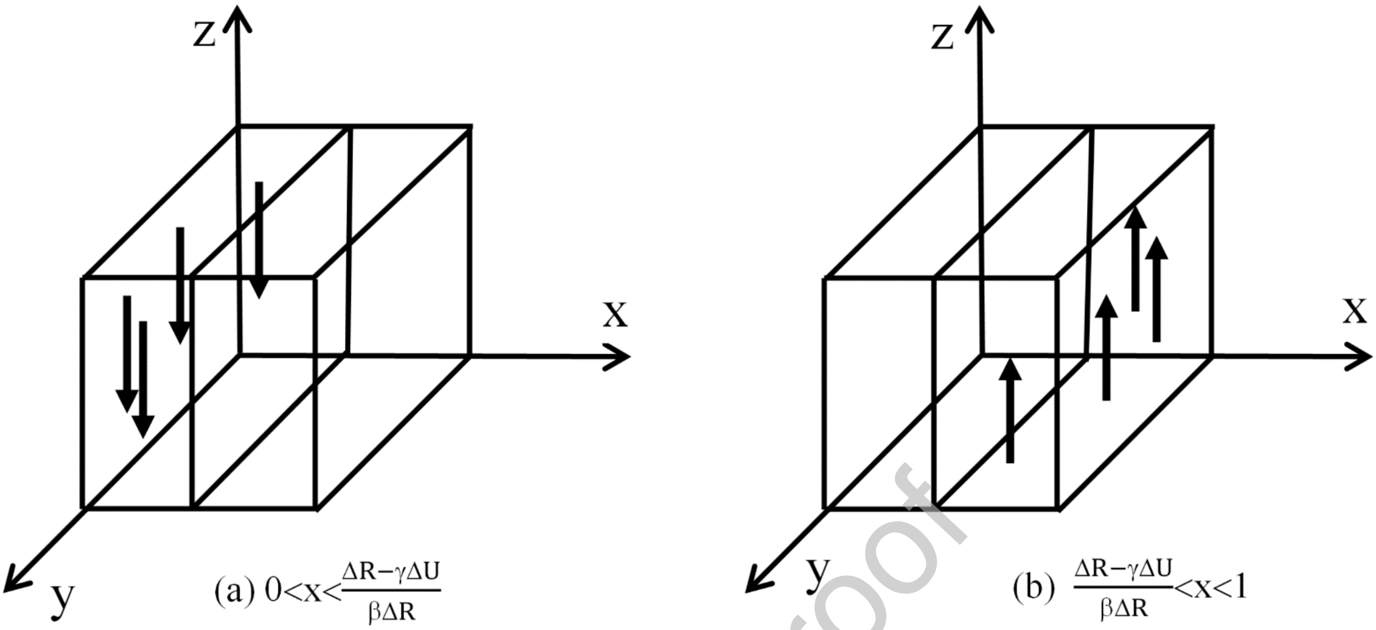
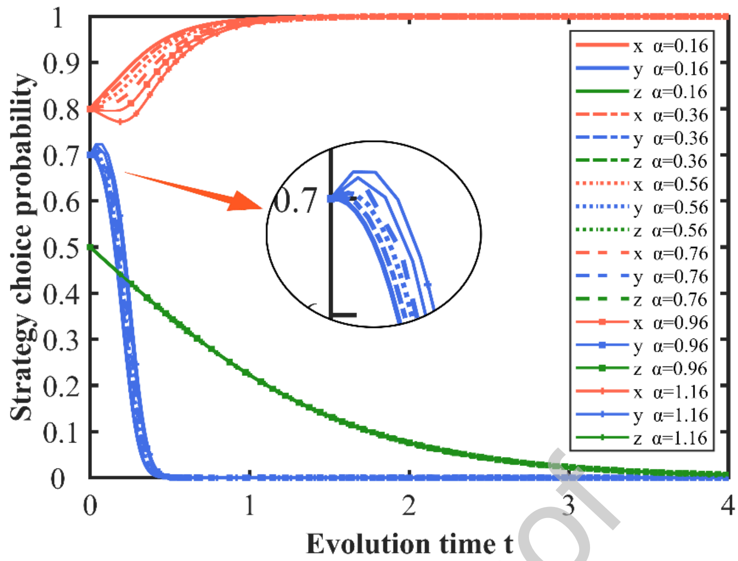
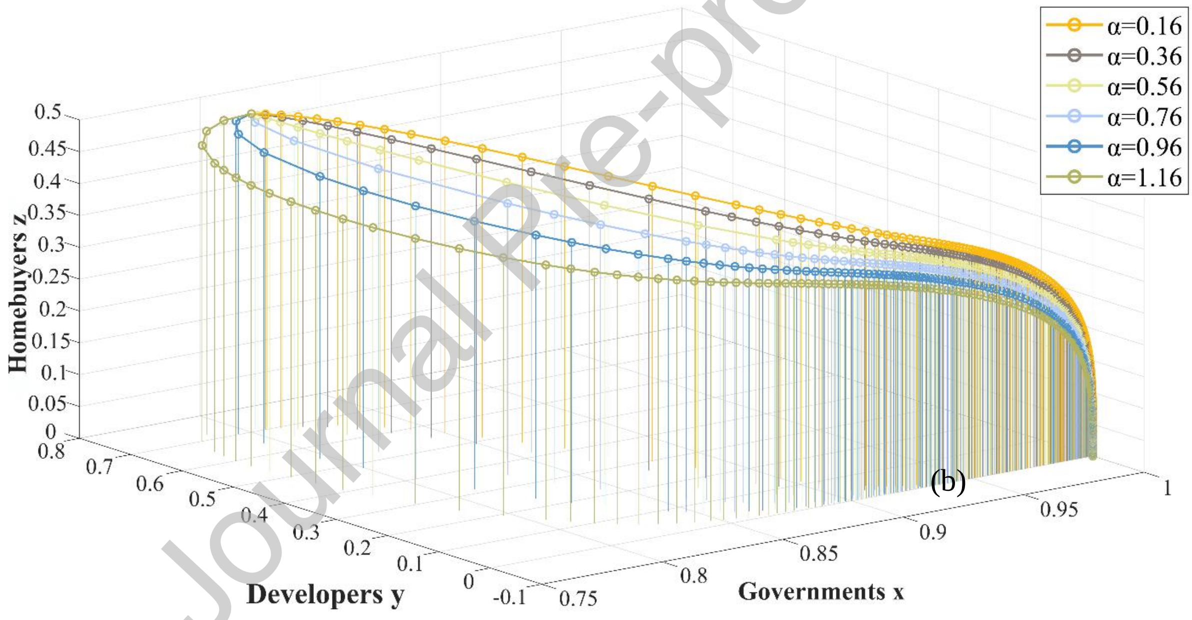


Figure 5. The evolutionary trajectory of homebuyer strategy

Figure 6. The case project



(a)



(b)

Figure 7. Decision evaluation of government (*x*), developer (*y*), and homebuyer (*z*) when green building subsidy is only provided to developers.

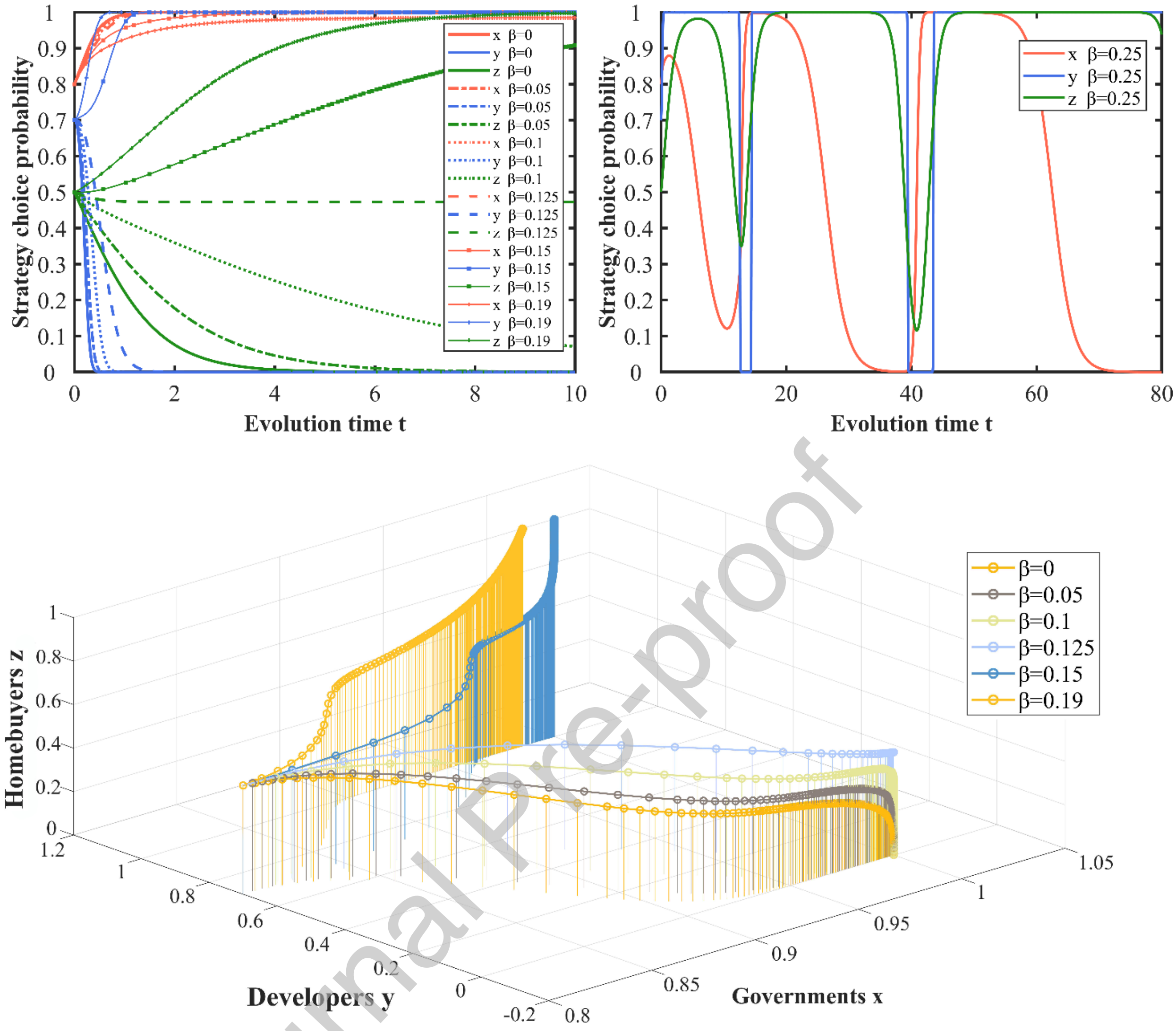


Figure 8. Decision evaluation of government (x), developer (y), and homebuyer (z) when green building subsidy is only provided to homebuyers.

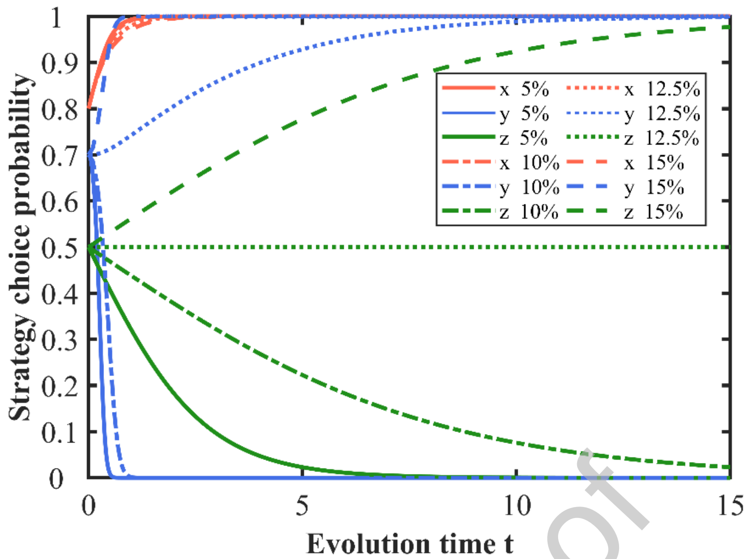


Figure 9. Decision evaluation of developer (*y*) and homebuyer (*z*) under price control

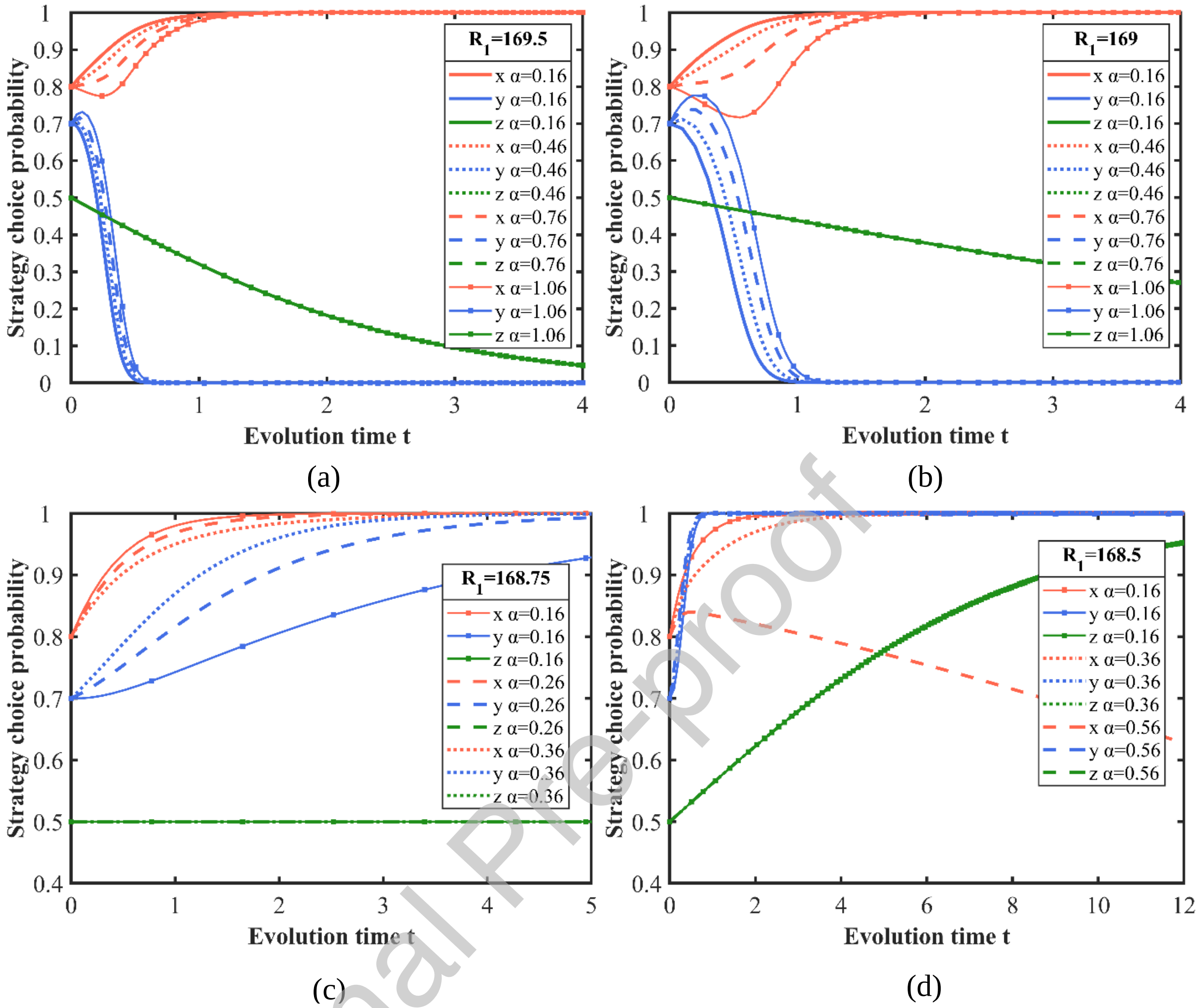


Figure 10. Decision evaluation of government (*x*), developer (*y*), and homebuyer (*z*) when subsidy is provided to developers and premium is reduced.

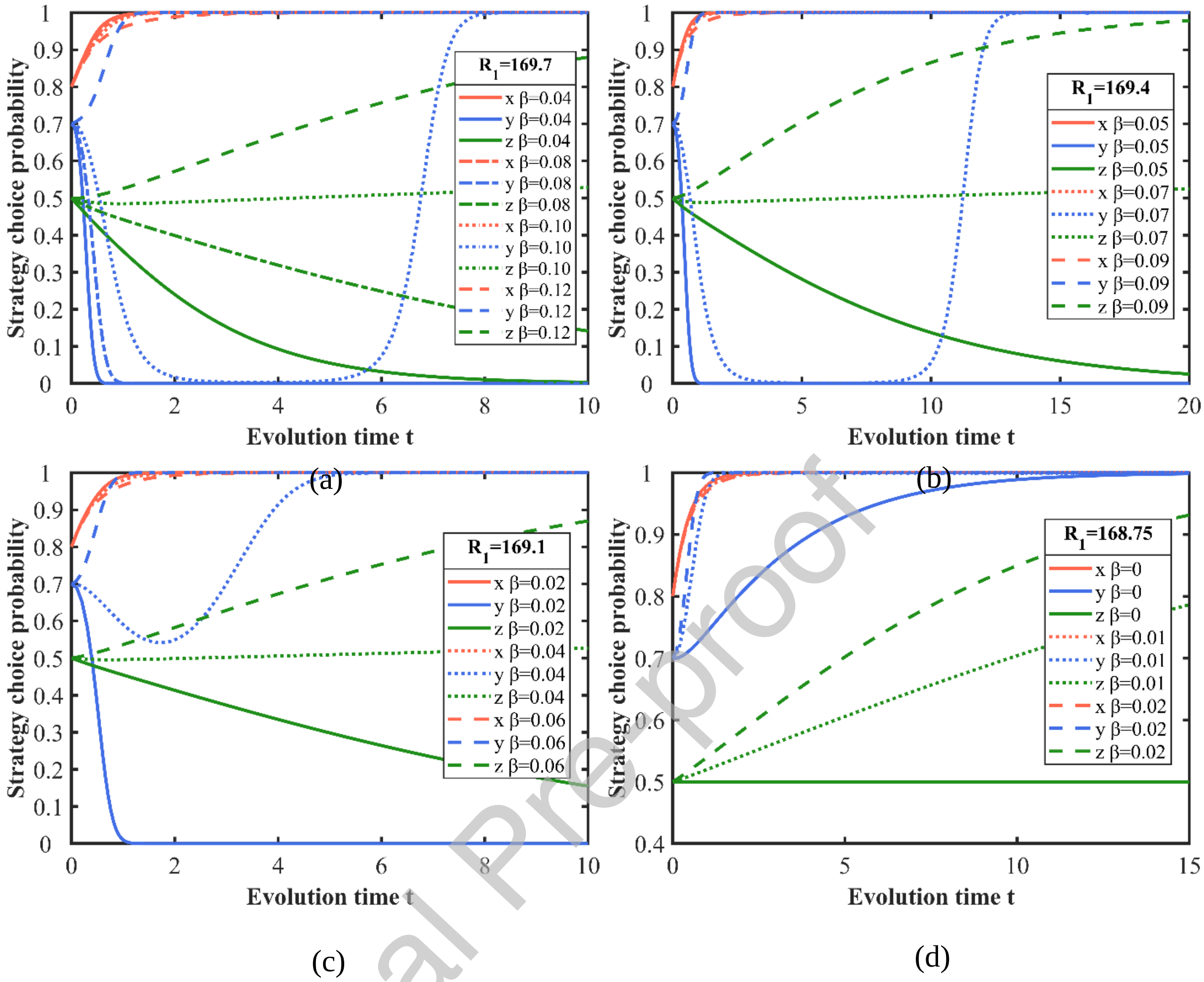


Figure 11. Decision evaluation of government (*x*), developer (*y*), and homebuyer (*z*) when subsidy is provided to homebuyer and premium is reduced.

Table 1. List of Variables in the Game

Variable	Description
R_1	The price to purchase a green building home (GB)
R_2	The price to purchase a conventional building home (non-GB)
ΔR	The premium to purchase green building, $\Delta R=R_1-R_2>0$
C_1	The cost to develop a green building home (GB)
C_2	The cost to develop a conventional building home (non-GB)
ΔC	The incremental cost to develop green building, $\Delta C=C_1-C_2>0$
U_1	The benefit of living in a green building (GB)
U_2	The benefit of living in a conventional building (non-GB)
ΔU	The marginal benefit to live in a green building, $\Delta U=U_1-U_2>0$
S	The societal benefits when offering green building subsidy, e.g., reputation gains for a government agency
T	The penalty to develop conventional buildings over green buildings, e.g., carbon tax or energy tax
α	The proportion of increment cost shared by government subsidy
β	The proportion of premium shared by government subsidy
γ	The level of awareness about the environmental, societal, and life-cycle cost benefits of green buildings
k	The tax rate that developers need to pay
x	The probability of the government choosing to offer GB subsidy
y	The probability of developers choosing to build GB projects
z	The probability of homebuyers choosing to purchase GB home

Table 2. Payoff Matrix for the Players

Payoff	Government	Developer	Homebuyer
$(1,1,1)$	$kR_1 + S - \alpha\Delta R$	$(1-k)R_1 - C_1 + \alpha\Delta C$	$U_2 + \gamma\Delta U - R_1 + \beta\Delta R$
$(1,1,0)$	$S - \alpha\Delta C$	$\alpha\Delta C - C_1$	$U_2 - R_2$
$(1,0,1)$	$S + T$	$-C_2 - T$	$U_2 + \gamma\Delta U - R_1 + \beta\Delta R$
$(1,0,0)$	$kR_2 + S + T$	$(1-k)R_2 - C_2 + T$	$U_2 - R_2$
$(0,1,1)$	kR_1	$(1-k)R_1 - C_1$	$U_2 + \gamma\Delta U - R_1$
$(0,1,0)$	0	$-C_1$	$U_2 - R_2$
$(0,0,1)$	0	$-C_2$	$U_2 + \gamma\Delta U - R_1$
$(0,0,0)$	kR_2	$(1-k)R_2 - C_2$	$U_2 - R_2$

Table 3. List of Variable Values and Explanations in Case Study

Variable	Explanation
ΔC=5×10^2 CNY/m^2	According to the project data
R_1=170×10^2 CNY/m^2	According to the house price data, R_1=170×10^2 CNY/m^2
R_2=160×10^2 CNY/m^2	In China, the premium of green-certified projects compared with non-green certified projects is 6.9% (Zhang et al., 2017), it can be inferred that the price of surrounding conventional houses is about R_2=160×10^2 CNY/m^2.
ΔR=10×10^2 CNY/m^2	ΔR=R_1 −R_2=10×10^2 CNY/m^2
ΔU=12.5×10^2 CNY/m^2	Green buildings can generate benefits 10 times as great as incremental cost (Kats, 2003). Based on the 2015 National Green Building Evaluation and Labeling Statistics Report, the incremental cost of three-star GB is 125. So set incremental benefits to be ΔU=12.5×10^2 CNY/m^2
T=1.3×10^2 CNY/m^2	Every square meter of reinforced concrete buildings emits 3.16 tons of carbon dioxide during a 50-year service life (You et al., 2011). The Ministry of Finance recommends that the carbon tax rate for 2020 be set at 40 CNY/t. So T=1.3×10^2 CNY/m^2
S=2.7×10^2 CNY/m^2	As there are few studies to quantitatively measure the social benefits of green buildings, we borrow the data of (Chen et al., 2021) here.
α=0.16	In 2012, the "Implementation Opinions on Accelerating the Development of my country's Green Buildings" was issued, which determined the award standard for three-star green buildings of 80 CNY/m^2. So, the initial value of α is 0.16.
γ=0.7	(Ofek & Portnov, 2020) conducted a questionnaire survey of 438 potential home buyers. 26%-31% of them are unaware of the benefits of reducing water and energy. Based on this, we set a reasonable value of γ=0.7.
k=0.25	(Chen et al., 2021) was in accordance with the "Regulations for the Implementation of the Enterprise Income Tax Law of the People's Republic of China", the income tax is 25%. Set k=0.25.