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Research on Dynamic Simulation of Multi-Agent Decision-Making in Passive Housing Based on Evolutionary Game Theory

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ABSTRACT

Passive House is a building standard that minimizes active energy consumption through optimal building design, the use of high- performance materials and efficient energy systems. However, compared with traditional housing, passive housing requires a higher upfront investment, which enterprises, local farmers and other households must bear. Due to differences in the interests of government, enterprises and farmers, a complex game-theoretical relationship will emerge during the decision-making process. For this reason, this paper takes an evolutionary game perspective on dynamic simulation of passive housing multi-agent decision-making, combining eight decision-making situations. Through constructing a perceived benefit matrix and conducting single-subject and tripartite- subject evolutionary game analyses, it was found that actively guiding by the government, active participation by enterprises and active cooperation by farmers helps to realize the construction of passive housing projects under ideal conditions.

Keywords: Passive House;Evolutionary Game; Multi-Agent Decision-Making Behavior

1. INTRODUCTION

With the rapid development of the global economy, the level of energy consumption has been rising steadily. Among them, residential buildings account for approximately 35% of the total energy consumption[1].Therefore, using passive technologies to improve house design is a better decision for energy conservation.By combining solar energy, ground source heat pump and other technologies, passive housing can further realize energy self-sufficiency, and even achieve "zero energy consumption" or "positive energy consumption"[2]. Through super insulation, airtight design, thermal bridge-free construction, etc., it reduces the exchange of heat between indoor and outdoor[3-4]. Heating and cooling energy consumption is typically 70% to 90% lower than in conventional buildings[5], and even eliminates the need for conventional heating systems in mild climates.It can be seen that passive houses can significantly reduce the energy consumption of buildings, thereby lowering carbon emissions and contributing to carbon neutrality[6-7]. Passive houses directly reduce greenhouse gas emissions by reducing dependence on fossil energy, which is environmentally friendly and energy efficient, and meets the dual needs of contemporary society for improved housing quality and sustainable development[8].

Therefore, in the long run, the large-scale popularization of passive housing is of great significance to both the construction of new rural areas and sustainable development. However, the decision-making process of passive house construction is influenced by the interests of different subjects, and there is a game relationship between the government, enterprises and farmers. Although the initial construction cost may be 5-15% higher than that of traditional buildings, its ultra-low energy consumption characteristics can save more than 80% of energy costs, while the incremental cost can usually be recovered within 10-20 years[9-11].

In the construction of new rural areas, it is necessary to coordinate the interests of multiple subjects in the construction of passive house.This paper analyzes the dynamic simulation research of multi-agent decision-making of passive house from the perspective of evolutionary game theory, guiding all parties to make decision-making behaviors conducive to the realization of the overall goal.

2. DEFINITION OF MULTI-AGENT DECISION-MAKING BEHAVIOR IN PASSIVE HOUSING

Under the background of the development of passive houses, the government, enterprises and families are the main participants. The decision-making behaviors of the government can be divided into two categories: "active encouragement" and "passive encouragement". The first approach is for the government to encourage enterprises

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to develop passive housing by implementing tax incentives, subsidies and related policies. The carbon trading mechanism can leverage private sector investment by 4 to 6 times, which can better help increase farmers' acceptance of passive housing[12-14].The latter approach signifies the government's non-interference in the attitudes and actions of businesses and households towards passive housing.

The behaviour of businesses is categorized as either "active participation" or "passive participation". Actively respond to relevant policies, actively develop passive housing, and take into account the social, ecological and economic benefits of passive housing[13]. In contrast, the latter approach is economically benefit-oriented and passive houses will only be built when there is a clear need. The decision-making behaviors of farmers can be divided into two categories: "active cooperation" and "non-cooperation". The research finds that the former has a higher acceptance of passive housing, is willing to participate in the transaction behavior of the passive housing market, and tends to bear some additional costs. In contrast, the latter group of people have a lower acceptance of passive housing, are reluctant to bear additional costs and purchase housing, and do not participate in market transactions. Constructing a cost-sharing model of "government subsidies + enterprise concessions + farmers" self-payment" can shorten the payback period of farmers' investment to 8 years, while the traditional model is 12 years[15]. In conclusion, we can construct multi-agent decision-making behaviors. The schematic diagram of the three-party evolutionary game is shown in Figure 1.

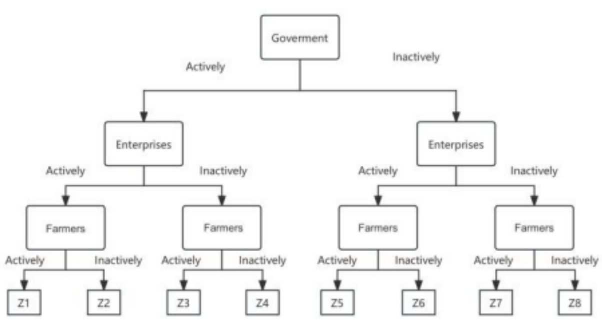

Fig. 1 Schematic diagram of the three-party evolutionary game

As illustrated in Figure 1, there are eight scenarios of passive housing multi-agent decision-making based on evolutionary games(Z_1-Z_8).

3. AN EVOLUTIONARY GAME MODEL FOR MULTI-AGENT DECISION MAKING

3.1 Basic assumptions and parameter definitions

In order to reliably analyze the evolutionary game of passive housing multi-agent decision-making, the following assumptions must be made in advance:

Assumption 1: Multi-agent decision-making behaviour in passive housing is limited rationality.

Assumption 2: The passive housing multi-agent evolutionary game period is characterized by continuous learning and game adjustment, automatic decision-making behaviour, and the process of reaching a stable state. This process can be replicated through the dynamic equation for evolutionary simulation.

Assumption 3: It is posited that there are two distinct categories of decision-making behaviors exhibited by all three subjects. The probability of the government's decision-making behaviour is defined at the inception of the game as x (actively guided) and 1-x (inactively guided). In a similar manner, the probabilities of enterprise and farmer decision-making behaviors can be defined as y and 1-y , and z and 1-z .

Based on the passive housing multi-agent identity attributes and their decision-making behavior to define the relevant parameters in the three-party subject evolutionary game are shown in Table1.

Subject Type	Paramete	Parameter Definition
Government	α	Government guidance intensity
	P	Related fines for non–"passive housing" projects
	U_1	Environmental governance cost for non–"passive housing" projects
	U_2	Additional costs due to farmers' non–cooperation
	β	Government supervision intensity for "passive housing" project construction
	γ	Penalty intensity for non–"passive housing" projects
	M	Additional supervision costs for non–"passive housing" projects
	E_1	Benefits of guiding enterprises to participate in "passive housing" projects
	E_2	Benefits of guiding farmers to cooperate with "passive housing" projects
	C_1	Incremental cost of proactive guidance
	T_1	Government incentives for enterprises participating in "passive housing" projects
	T_2	Government incentives for farmers cooperating with "passive housing" projects
Enterprises	Q_1	Additional benefits to enterprises from farmers' active cooperation
	U_3	Additional costs to enterprises from farmers' non–cooperation
	E_3	Benefits of enterprises participating in "passive housing" projects
	E_4	Benefits of enterprises participating in "traditional housing" projects
	C_2	Incremental cost for enterprises participating in "passive housing" projects
Farmers	Q_2	Additional benefits to farmers from enterprises' participation in "passive housing"
	U_4	Additional benefits to farmers from enterprises' participation in "passive housing"
	C_3	Incremental cost for farmers actively cooperating with "passive housing" projects
	E_5	Benefits for farmers actively cooperating with "passive housing" projects
	E_6	Benefits for farmers not actively cooperating with "passive housing" projects

Table 1 Definitions and descriptions of parameters in the tripartite evolutionary game model.

3.2 Constructing the Perceived Benefits Matrix

In the context of passive housing multi-agent decision-making at Z_1, the government plays an active role in facilitating the participation of enterprises, while farmers collaborate actively in the construction of "passive housing" projects. The positive decision-making behaviour of enterprises and farmers will bring additional benefits to the government, but at the same time, it will also lead to additional incentive and regulatory costs for the government.Enterprises should be aware that participation in the construction of "passive house" projects will incur additional costs. However, it is important to note that government guidance and collaboration with farmers will also bring enterprises additional benefits.

From the perspective of farmers, participation in the project entails a cost, but the "passive housing" will also enhance their quality of life and generate additional benefits.Furthermore, the overall multi-agent returns for other passive housing multi-agent decision-making scenarios can be obtained, as demonstrated in Table 2.

Subject Type	Government	Enterprises	Farmers
Z_1	$E_1+E_2-C_1-\beta M-\alpha(T_1+T_2)$	$Q_1+E_3-C_2-\beta M+\alpha T_1$	$Q_2+E_5-C_3+\alpha T_2$
Z_2	$E_1-C_1-U_2-\beta M-\alpha T_1$	$\alpha T_1+E_3-\beta M-U_3-C_2$	E_6
Z_3	$E_2-C_1-U_1-\alpha T_2-\gamma P$	$E_4-\gamma P$	$\alpha T_2+E_5-C_3-C_4$
Z_4	$\gamma P-U_1-U_2-C_1$	$E_4-\gamma P-U_3$	E_6-E_4
Z_5	0	$Q_1+E_3-C_2$	$E_5-C_3+Q_2$
Z_6	$-U_2$	$E_3-C_2-U_3$	E_6
Z_7	$-U_1$	E_4	$E_5-U_4-C_3$
Z_8	$-U_1-U_2$	E_4-E_3	E_6-E_4

Table 2 Statistics on the overall returns of passive housing multi-agent under different decision scenarios

4. EVOLUTIONARY GAME ANALYSIS OF MULTI-AGENT DECISION MAKING IN PASSIVE HOUSING

4.1 Government Evolution Game Analysis

Based on the above analysis can be constructed the replication dynamic equation of governmental decision-making behavioral choices as follows:

$$F(x)=x[G_{11}-(xG_{11}+G_{12}-xG_{12})]\#(1)$$

$$F(x)=x(1-x)[y(E_1-\beta M-\gamma P-\alpha T_1)+\gamma P-C_1+z(E_2-\alpha T_2)\#(2)$$

In equation (1) , G_{11}denotes the expected return under positively guided decision-making behavior by the government. G_{12} denotes the expected return in the event that the government does not actively guide decision-making behavior.

Similarly, the stabilization of decision-making behavior under the enterprises' evolutionary game requires that both $\frac{dF(x)}{dx}<0$and $F(x)=0$ are satisfied.

When $y\neq y^*$,let equation (2) be equal to zero.The two solutions of the equation can be obtained as 0 and 1. At this point the first order derivatives of x can be further obtained.

$$F'(x)=(1-2x)[y(E_1-\beta M-\gamma P-\alpha T_1)+\gamma P-C_1]+z(E_2-\alpha T_2]\ \#(3)$$

Let $L(y)=y(E_1-\beta M-\gamma P-\alpha T_1)+\gamma P-C_1+z(E_2-\alpha T_2)$ .The derivative shows that $L(y)$ is an increasing function.At this point the solution of $F(x)$is discussed separately for the $y<y^*$ and $y>y^*$ cases.

In case $y<y^*$, $\left.\frac{dF(x)}{dx}\right|_{x=0}<0,\left.\frac{dF(x)}{dx}\right|_{x=1}>0,$,at which point the solution to $F(x)$ is 0.Suggests that it is appropriate for the government to take no active role in guiding decision-making.

In case $y>y^*$, $L(y)$ is constantly greater than zero, $\left.\frac{dF(x)}{dx}\right|_{x=0}>0,\left.\frac{dF(x)}{dx}\right|_{x=1}<0,$,at which point the solution to $F(x)$ is 1, indicating that it is appropriate for the government to take an active role in guiding the decision.

In addition,when $y=y^*$, $F(x)$is constant zero.This suggests that the government's expected return remains constant irrespective of the decision taken.

The preceding analysis suggests the following inference: The probability of the government adopting an active guiding decision is negatively related to the incremental cost it bears. Conversely, it is positively correlated with the additional benefits derived from the active participation of enterprises and the cooperation of farmers.

Consequently, when the incremental cost to enterprises of participating in the Passive House program diminishes, or when the benefit to the government of guiding enterprises to participate in the Passive House program amplifies,the probability that the government will take a proactive decision escalates.

4.2 Enterprise Evolution Game Analysis

In accordance with the preceding analysis, it is feasible to establish a replicated dynamic equation for the choice of enterprises' decision-making behaviour, which is outlined as follows:

$$F(y)=y[M_{11}-(yM_{11}+M_{12}-yM_{12})]\#(4)$$

$$F(y)=y(1-y)[x(\gamma P+\alpha T_1-\beta M)+E_3+zQ_1-E_4-C_2)\#(5)$$

In equation (4), M_{11} indicates the expected return under the active participation of enterprises in decision-making behavior. M_{12} denotes the expected return under the behavior of enterprises that are not actively involved in decision making.Similarly, the stabilization of decision- making behavior under enterprises' evolutionary game requires that both $\frac{dF(y)}{dy}<0$ and $F(y)=0$ conditions are satisfied.

When $z\neq z^*$,let equation (5) be equal to zero.The two solutions of the equation can be obtained as 0 and 1. At this point the first order derivatives of y can be further obtained.

$$F'(y)=(1-2x)[x(\gamma P+\alpha T_1-\beta M)+E_3+zQ_1-E_4-C_2]\ \#(6)$$

Let $K(z) = x(\gamma P + \alpha T_1 - \beta M) + E_3 + zQ_1 - E_4 - C_2$,the derivative shows that $K(z)$ is an increasing function.At this point the solution of $F(y)$ is discussed separately for the $z < z^*$ and $z > z^*$ cases.

In case $z < z^*$, $\left.\frac{dF(y)}{dy}\right|_{y=0} < 0, \left.\frac{dF(y)}{dy}\right|_{y=1} > 0$, at which point the solution to $F(y)$ is 0. This suggests that a non-participatory approach to decision-making is appropriate for enterprise.

In case $z > z^*$, $K(z)$ is constantly greater than zero, $\left.\frac{dF(y)}{dy}\right|_{y=0} > 0, \left.\frac{dF(y)}{dy}\right|_{y=1} < 0$, at which point the solution to $F(y)$ is 1. It is suggested that the enterprise should adopt a proactive approach to decision-making.

In addition,in case $z = z^*$, $F(y)$ is constant zero.It is imperative to elucidate the notion that enterprises' anticipated returns remain constant irrespective of the decision made.

In light of the aforementioned analyses, the following conclusions can be drawn: the probability of a enterprise engaging in proactive decision-making is negatively correlated with the cost of the decision, while the benefits to the enterprise of active participation in the project, as well as the additional benefits from farmers' cooperation, are positively correlated with each other. Consequently, as the benefits to the enterprise of active participation in the 'passive housing' project increase, so does the probability of the enterprise engaging in proactive decision-making.

4.3 Farmers Evolution Game Analysis

Based on the above analysis it is possible to construct a replicated dynamic equation for the choice of decision-making behavior of farmers as follows:

$$F(z) = z[T_{11} - (zT_{11} + T_{12} - zT_{12})] \#(7)$$

$$F(z) = z(1-z)(x\alpha T_2 + yQ_2 + E_5 - E_6 - C_3) \#(8)$$

In equation (7), T_{11} denotes the expected return under the positive cooperation decision- making behavior of farmers. T_{12} denotes the expected return under the farmer's behavior of not actively cooperating in decision making.Combined with the principle of stability of replicated dynamic differential equations, it can be seen that their stability requires that both $\frac{dF(z)}{dz} < 0$ and $F(z) = 0$ conditions are satisfied.

When $x \neq x^*$,let equation (8) be equal to zero.The two solutions of the equation can be obtained as 0 and 1. At this point the first order derivatives of z can be further obtained.

$$F'(z) = (1-2z)(x\alpha T_2 + yQ_2 + E_5 - E_6 - C_3) \#(9)$$

Let $J(x) = x\alpha T_2 + yQ_2 + E_5 - E_6 - C_3$, the derivative shows that $J(x)$ is an increasing function.At this point the solution of $F(z)$ is discussed separately for the $x < x^*$ and $x > x^*$ cases.

In case $x < x^*$, $\left.\frac{dF(z)}{dz}\right|_{z=0} < 0, \left.\frac{dF(z)}{dz}\right|_{z=1} > 0$, ,at which point the solution to $F(z)$ is 0. It suggests that it is appropriate for farmers to take a decision not to actively cooperate.

In case $x > x^*$, $J(x)$ is constantly greater than zero, $\left.\frac{dF(z)}{dz}\right|_{z=0} > 0, \left.\frac{dF(z)}{dz}\right|_{z=1} < 0$, at which point the solution to $F(z)$ is 1. It suggests that it is appropriate for farmers to take positive cooperation decisions.

In case $x = x^*$, $F(z)$ is constant zero. It shows that farmers' expected returns do not change no matter which decision they take.

The above analysis leads to the following inference: the probability of farmers making an active cooperation decision is negatively correlated with the incremental costs they pay under this decision and positively correlated with the additional benefits enterprises bring to farmers through active participation and the additional benefits obtained through farmers' active cooperation. Therefore, when the incremental cost paid by farmers for active cooperation in the Passive House program decreases, the probability of them adopting this decision will increase.

4.4 Tripartite evolutionary game model

Jointly Eq. (2), Eq. (5), and Eq. (8), let $F(x) = F(y) = F(z) = 0$,eight equilibrium points can be obtained, corresponding to the eight scenarios of passive housing multi-agency decision-making, see Table 3.

Multi-agent Decision-Making Situations	Balance Point
Z_1	$S_1(1,1,1)$
Z_2	$S_2(1,1,0)$
Z_3	$S_3(1,0,1)$
Z_4	$S_4(1,0,0)$
Z_5	$S_5(0,1,1)$
Z_6	$S_6(0,1,0)$
Z_7	$S_7(0,0,1)$
Z_8	$S_8(0,0,0)$

Table 3 Correspondence Between Equilibrium Points and Multi-Agent Decision-Making Scenarios

The stability of each stable point was determined by substituting it into the Jacobi matrix and calculating the eigenvalues.

$$A = \begin{bmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} & \frac{\partial F(x)}{\partial z} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} & \frac{\partial F(y)}{\partial z} \\ \frac{\partial F(z)}{\partial x} & \frac{\partial F(z)}{\partial y} & \frac{\partial F(z)}{\partial z} \end{bmatrix} \#(10)$$

According to Lyapunov stability theorem it is known that the equilibrium point is a stable node when all the characteristic roots of the Jacobi matrix are negative.

Bringing the equilibrium point into the Jacobi matrix, it is found that when all three parties, government, enterprises and farmers, take positive decisions, then there is:

$$\begin{cases} \alpha T_1 + \alpha T_2 + C_1 + \beta M - E_1 - E_2 < 0 \\ C_2 + \beta M + E_4 - Q_1 - \alpha T_1 - E_3 - \gamma P < 0 \\ C_3 + E_6 - \alpha T_2 - Q_2 - E_5 < 0 \end{cases} \#(11)$$

At this point, the benefits to the three parties outweigh the costs, which is the ideal state for constructing passive housing projects. However, under the multi-agent decision-making model, there is a certain 'free-rider' phenomenon whereby some parties are not willing to invest resources. Although equilibrium can be achieved, this has a negative impact on overall development.

5.CONCLUSION

The dynamic simulation of passive housing multi-agent decision-making based on the evolutionary game finds that only when the government, enterprises and farmers all make positive decisions, it is conducive to realizing the optimal decision-making under the rational state, ensuring that the benefits of the multi-agent are greater than the expenditures.

The higher the additional benefits brought to farmers by the active participation of enterprises and the higher the additional benefits obtained by the active cooperation of farmers, the higher the probability of farmers adopting positive decision-making behavior. It can be seen that the probability of active decision-making behavior of the government, enterprises and farmers are all closely related to the additional benefits created by the participation of other subjects in the construction of passive housing projects. So in the construction of rural areas, government should speed up the formulation of passive housing construction policy documents, encourage the participation and cooperation of enterprises and farmers to form a virtuous circle of mutual promotion, and promote the effective promotion and application of passive housing in the construction of new rural areas. Passive housing can build a sustainable green building ecology through the tripartite synergy of government policy drive, enterprise technology empowerment, and farmer demand pull. Its core lies in transforming long-term environmental benefits into short-term economic incentives, and ultimately realizing the multiple goals of energy security, livelihood improvement and industrial upgrading.

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