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Abstract—**The process of green building development involves not only the symbiotic changes on the numbers of green and traditional buildings, but also the game payment of the agents. According to the symbiosis theory and evolutionary game theory, a symbiosis model of green building supply side is established, with the construction market carrying capacity considered. The evolutionary stable points and stability conditions of the symbiotic evolutionary model are analyzed and discussed. The results show that the stable condition of the symbiotic evolution between different agents in proposed symbiosis model depends upon the combination of the game payment of different agents, but has nothing to do with the reproduction rate. It is also shown that relaxing the cap on the upper limit or maximum volume of the construction market will lead to both the numbers of green buildings and the numbers of government incentives increase at the same time.**

Keywords-green building; density game analysis; symbiosis theory; evolutionary game; symbiotic evolution; coexistence; equilibrium dynamics; market carrying capacity

I. INTRODUCTION

Buildings have significant impacts on the environment, accounting for one-quarter of its wood harvest and two-fifths of its material and energy flow [5]. In the life cycle of buildings, the construction process, the operation stage and the disposal procedure, affect carbon gas emissions and energy consumption directly and indirectly [23]. Cities and urban areas are estimated to use 75% of the world's energy and produce up to 80% of its greenhouse gas emissions [13]. Green building, as a very important developing direction of the construction industry, maximizes resources (e.g. energy, land, water, etc.), protects the environment, reduces pollution, provides people with healthy, comfortable and efficient use of space, and is constructed in harmony with nature [20] .

Life cycle thinking on green building has recently gained considerable attention, accounting for the three pillars of sustainable development: environmental, economic, and social aspects [8]. Thatcher and Milner [26] found, comparing with traditional building, green buildings enabled significant improvements in perceived air quality, significant improvements in self-report productivity and significant improvement in physical well-being. Currently, more than 12.4 million square feet of building space in over 150 countries and territories participate in some form or adaptation of the LEED system and 1.85 million square feet of building space are certified by LEED per day around the world [20]. Green building incentives are categorized into external and internal ones. The external incentives are forced choice whereby beneficiaries are required to fulfill specified conditions or requirements before getting any benefits [19]. Although green building has many advantages, it has brought many changes, such as extra cost and management change. It is regarded that the perceived higher upfront cost by building owners and investors is a barrier to a widespread adoption of green buildings. However, the experimental analysis from Dwaikat and Ali [8] showed that consensus is not reached, and more than 90% of the reported green cost premiums through empirical investigations fall within a range from −0.4% to 21%. The similar result also came from Gabay et al.'s work. At the same time, Gabay's conclusion showed that the high rate of return on investment stems mostly from savings on electricity and increased worker productivity [9]. The social problem related to green building involves many aspects such as consumers' basic understanding, purchase intention, social and humanistic needs, public attitudes and behaviors, rebound effects and furthermore social acceptance [31]. By using ecological modernization (EM) framework, Zhou found that the top-down state apparatus is not sufficient to overcome the contradictions in green project and the profit motives of the property developers [32].

Green building project management is a very complicated process. Therefore, critical success factors is another important research area which academia should pay attention to. Lapinski, Horman, and Riley [15] discovered that five key value-added processes contribute to the successful delivery of GB projects: deciding to evaluate and adopt sustainable objectives at the very early stage of the project; identifying and pursuing building features that naturally align with sustainability; aligning sustainable objectives to the business case of the project; devoting time to align individual team member goals with project goals; and selecting an experienced design and construction team at the early phase of the project. Research from Azouz and Kim [3] showed that the main issues contractors revealed with the green building include increased time demand, fear of change, increased equipment costs, fear of auditing of construction documents and many more. In order to help projects achieve higher ratings of Green Mark effectively, Li et al. [16] conducted relevant work and identified the critical resources and capabilities of design firms. And "experience and knowledge in GB", "organizational green culture", "innovation capability" were found more important than other factors in their result. In the ranking of risk importance in green building, Qin et al. [20] found the top five key risk factors ranked to be: government bureaucracy and complicated approval procedures; inadequate GB maintenance; lack of GB design experience; lack of experienced property management during trial operation stage, and inaccurate orientation of project's green-goal. Thus, rough set theory and interactive networks were employed to investigate the conflict degree amongst various project objectives from stakeholder's point of view [25, 29, 30]. The results revealed that while reputation risk is important in China and Australia, the ethical risk of 'assessment experience and fairness' has been highlighted as crucial in the Chinese context, the results further show that government plays an important role in improving the societies' knowledge and awareness on green technology uptake in China [30].

In order to promote the progress of green building, some other management research in this area focus on the policy effect [10, 14, 22, 24], developing appropriate constructs to benchmark green building attributes [27], the assessing system of green building [11, 17, 23], the cost–benefit evaluation of energy efficiency technology application (EETA) on green buildings [18], "one-stop-shop" BIM for green building [28], future Research topics on green building project [7]. Despite growing awareness and recognition of green buildings, there is a lack of system dynamic studies on the symbiosis system between green building developers and the government. Out research aims to address and fill this gap of knowledge by establishing a theoretical symbiosis model that considers the payoff matrix between green developers and the government.

II. Symbiosis Model on Green Building with Considering Payoff Matrix

The basic idea of evolutionary game theory is that payoff determines reproductive rate. Successful individuals have a higher payoff and produce more offspring. Nevertheless, in evolutionary and ecological situations there is not only the reproductive rate but also the carrying capacity [21]. The density-dependent dynamic system became a very important direction in evolutionary research [1, 2, 4]. In order to combine the payoff matrix with competitive Lotka-Volterra equations, Sebastian presented the density game [21]. Further, Huang et al. proposed a stochastic model that naturally integrates these two evolutionary ingredients by assuming frequency-dependent competition between different types in an individual-based model [12]. The difference between Sebastian's model and Huang's model lies in the carrying capacity of individual phenotype.

A. *The Basic Assumption of Model*

According to the present situation of the construction management system, especially when considering the role of the construction department in reducing green gas emissions, several assumptions are made as the following.

There are two limited rationality agents. One is government department which decides whether encourage green building projects or not; the other is the developer which decided to develop green building projects or ordinary construction projects.

Developers can choose to develop green building projects or ordinary construction ones. Government departments can choose to incent or not.

Information for the agents in the model is incomplete.

Due to the delay characteristics of government approval, green building areas implemented by the developer themselves are different from those incented by the government.

Based on the above assumptions, the payoff matrix is shown in Table 1. Government departments can get benefits such as completion of the emission reduction targets F from the development of green building, the corresponding incentive cost of green building project is S (as for the S , it is further assumed that $S' > 0$, $S'' < 0$. This assumption means that when the government can benefit from the development of green building projects. They have the motives to provide incentives. The more the government benefits, the more rewards will be provided. Normally, in the initial stage, developers do not want to develop green building projects without incentives from the government such as land tax preferential policies or other bonus, in such a situation their earnings are P and r respectively. According to the national green building standards, the incremental cost of green building project is ΔC , and the expected incremental benefit of developer is R . According to the above mentioned conclusion on green building research, the failure probability of green building development is assumed f , if the green building project fails, the developers will loss H , $f*H$ is called incremental risk loss. Furthermore,assuming that a green building project incentive contract signed by the developer and the government department, if the developer cannot perform the contract for various reasons, and hence will be fined A by the government department for breaching the contract. Because all items in the payoff matrix do not affect the analysis results, so some of them are abbreviated in table 1 for analysis. The specific economic meaning of the corresponding payments are as follows, a means the profit per unit area on condition that the developer chooses a green building project and government chooses incentives. c means the incentive cost per unit area in the same condition; b is the profit per unit area only if the developer chooses a green building project and government does not implement incentives. d is the incentive cost per unit area within the situation that the developer does not choose a green building project and the government chooses incentives. Here a, b, c and d are required to be positive.

TABLE I. GAME PAYOFF OF SUPPLY SIDE IN GREEN BUILDINGS

		Government	
		Incentives	Disincentives
Developer	Green buildings	$r+R+S-\Delta C-f*H \square F-S$	$r+R-\Delta C-f*H \square \boldsymbol{F}$
	Ordinary buildings	$r+S-A,\ -S+A+P$	$\boldsymbol{r} \square P$

$$a=r+R+S-\Delta C-f*H;\ b=r+R-\Delta C-f*H;\ c=F-S;\ d=A+P-S$$

B. *Density Game of Green Building Supply Side*

The government and the developer are both agents with limited rationality on the base of limited knowledge and ability. According to the two premises and interests of these two in the process of green building development, it is natural that the main relationship between the government and the developer is parasitic symbiosis. If the developer disappeared, the government would also cease to incent. But without the incentives from the government, the developer can also choose to develop green building project. Based on the above mentioned analysis and combined the research work from Sebastian and Huang, after the carrying capacity is introduced, the equation of the density game in [24] changes as shown in the equation (1).

$$\begin{cases} \dfrac{dx_1}{dt}=r_1x_1\left(1-\dfrac{x_1}{a*M}+\dfrac{x_2}{b*M}\right) \\ \dfrac{dx_2}{dt}=r_2x_2\left(-1+\dfrac{x_1}{c*M}-\dfrac{x_2}{d*M}\right) \end{cases} \tag{1}$$

where populations $x_1(t)$ (abbreviated as x_1) is the area of green buildings implemented, populations $x_2(t)$ (abbreviated as x_2) is the area incented by the government which is the prey for populations x_1 and get its population continuous growth, if the prey populations is small enough, the predator population develop independently, which in turn will lead to the prey populations increase again, in turn lead to the growth of the predator populations, finally form the cyclical behavior process between the two populations. Parameter r_1 represents the net natural increase rate of the development behavior of green buildings; r_2 stands for the net natural increase rate of the incentive behavior from the government. Where M represents maximum volume of the construction market in specific area. Therefore, either the developer or the government is facing the same market. The carrying capacity $a*M$ can be interpreted as the total market profit when the government chooses to incent and the developer selects to develop a green building project. The carrying capacity $c*M$ can be interpreted as the total incentive cost under the same situation. Carrying capacity $b*M$ and $d*M$ can be interpreted by the same way. Parameter r_1x_1 and r_2x_2 respectively reflect the developing trend of the two agents in the green building supply side system, the logistic coefficient $1-\dfrac{1}{a*M}$ and $-1-\dfrac{1}{d*M}$ are their own growth retardation coefficient because of their consumption of limited social resources respectively.

C. *Stability analysis of the model*

1) Equilibrium *stability analysis of the density game model*

Equilibrium stability analysis of equation (1) should be developed in order to explore the symbiotic evolution characteristics of different agents shown in equation (1). According to the stability theory of ordinary differential equations, the equation (1) have four partial equilibrium, which are respectively $E_1(0,0)$, $E_2(Ma,0)$, $E_3(0,-Md)$, $E_4\left(\dfrac{Mac(b-d)}{bc-ad},\dfrac{Mbd(a-c)}{bc-ad}\right)$. Among the partial equilibrium, $E_3(0,-Md)$ has not practical means, E_4 is the equilibrium point of coexistence of two agents, and is the focus of the study. Stability analysis is mainly based on the combined symbols of the determinant and trace of Jacobian matrix in an ordinary equation. Correspondingly, the Jacobian matrix of equation (1) is shown in the formula (2).

$$J=\begin{bmatrix} r_1+\dfrac{r_1(ax_2-2bx_1)}{Mab} & \dfrac{r_1x_1}{Mb} \\ \dfrac{r_2x_2}{Mc} & -r_2-\dfrac{r_2(2cx_2-dx_1)}{Mcd} \end{bmatrix} \tag{2}$$

The corresponding determinant value of the matrix can be calculated based on equation (2), the calculation results is shown in the formula (3).

TABLE II. EQUILIBRIUM AND STABILITY ANALYSIS ON LAW OF THE JUNGLE MODEL

Equilibrium	$\det J$	trJ	Stability conditions
$E1(0,0)$	$-r1*r2$	$r1-r2$	Unstable
$E_2(Ma,0)$	$r_1r_2(c-a)/c$	$r_2(a/c-1)-r_1$	$c>a$
$E_3(0,-Md)$	$r_1r_2(b-d)/b$	$r_1(1-d/b)+r_2$	NA
$E_4\left(\dfrac{Mac(b-d)}{bc-ad},\dfrac{Mbd(a-c)}{bc-ad}\right)$	$\dfrac{r_1r_2(a-c)(b-d)}{bc-ad}$	$\dfrac{r_1c(b-d)+r_2b(a-c)}{bc-ad}$	$\operatorname{sgn}(bc-ad)=\operatorname{sgn}(a-c)=\operatorname{sgn}(b-d)$

$$\det J = -\left(r_1 + \frac{r_1(ax_2 - 2bx_1)}{Mab}\right)*\left(r_2 + \frac{r_2(2cx_2 - dx_1)}{Mcd}\right) - \frac{r_2x_2}{Mc}*\frac{r_1x_1}{Mb} \quad (3)$$

In the same way, the corresponding trace of the matrix can be calculated based on equation (2), the calculation results is shown in the formula (4).

$$trJ = -\left[\left(r_1 + \frac{r_1(ax_2 - 2bx_1)}{Mab}\right) - \left(r_2 + \frac{r_2(2cx_2 - dx_1)}{Mcd}\right)\right] \quad (4)$$

The symbiotic evolutionary stable point of different agents in supply side system of green building can be analyzed according to the equation (2) and (4). Based on the stability theory of ordinary differential equations, the equilibrium goes into the asymptotic stable state when $trJ > 0$ and $\det J > 0$. The determinant symbol, mark symbol and the analysis of stability conditions of the equilibrium point of the supply side density game model on green building are shown in table 2. Where $E1(0,0)$ is unstable points; $E_2(Ma,0)$ is a equilibrium point that represents surviving of the investment behavior but extinction of government incentive behavior; and E_4 is coexistence point of two agents that is the thesis research priorities. Considering the serious green gas emission situation, the development of green buildings is an very important measure of energy saving and emission reduction for the government, and for a long time the incentives for green buildings cannot be canceled. Therefore the investment behavior in green building is unlikely to become extinct. There will be more and more green building areas. It is shown in table 2 that the coexistence condition is that $\operatorname{sgn}(bc - ad)$, $\operatorname{sgn}(a - c)$, $\operatorname{sgn}(b - d)$ have the same symbols. But from a practical view, the unit area incentive cost from the government cannot be greater than the profit per unit area, so it can be viewed that $\operatorname{sgn}(a - c)$ is positive, and the same to $\operatorname{sgn}(b - d)$.

2) Chart analysis of the density game model

Equation (1) shows that the change of dynamic system is mainly determined by the value expression in brackets. Therefore, according to the equation (1), the expression of equation (6) is shown below.

$$\begin{cases} \phi(x_1, x_2) = 1 - \dfrac{x_1}{a*M} + \dfrac{x_2}{b*M} \\ \Psi(x_1, x_2) = -1 + \dfrac{x_1}{c*M} - \dfrac{x_2}{d*M} \end{cases} \quad (5)$$

It can be seen from the equation (5) that the range of agent x_1 and that of agent x_2 are different. And the phase stability analysis of the point E_4 is shown in Fig. 1. In area D_1, the evolutionary characteristics of the two agents are $\phi < 0$, $\Psi > 0$ which means that the growth rate of green buildings dx_1/dt is less than zero and the growth rate of government incentives dx_2/dt is greater than zero. Staring from area D_1, chart point moves up and left, when the chart point meets the line $\Psi = 0$ which means $\phi < 0$ and $\Psi = 0$, then the chart point moves left and into area D_2, Similarly, when chart point meets the line $\phi = 0$ which means $\Psi > 0$ and $\phi = 0$, then the chart point moves up and into area D_4. Starting form this region, the phase point tends to be stable at E_4 or enters into area D_2 or area D_4.

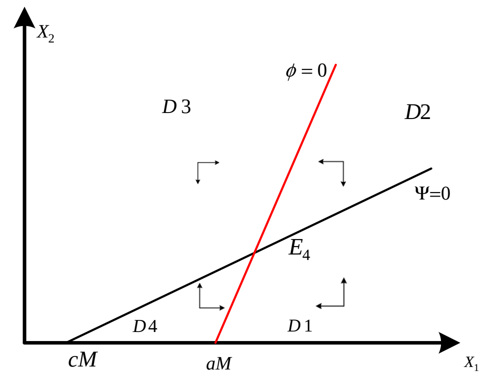

Figure 1. Chart analysis of point E_4

In area D_2, the evolutionary characteristics of the two agents are $\phi < 0$, $\Psi < 0$ that means the growth rate of agent dx_1/dt is less than zero and the same to that of agent dx_2/dt. Starting from area D_2, the phase point moves down and left, which tends to be stable at point E_4.When the chart point meets the line $\Psi = 0$ which means $\phi < 0$ and $\Psi = 0$, then the chart point moves left, which cannot enter area D_1. The same happens when the chart point meets the line $\phi = 0$ which means $\Psi < 0$ and $\phi = 0$, then the chart point moves down and cannot enter area D_3. So, in this area, the chart point only tends to be stable at point E_4.

In area D_3, the evolutionary characteristics of the two kinds agents are $\phi > 0$ □ $\Psi < 0$ which means that the growth rate of agent dx_1/dt is greater than zero and that of agent dx_2/dt is less than zero. Starting from this area, chart point moves down and right, when the chart point meets the line $\Psi = 0$ that means $\phi < 0$ and $\Psi = 0$, then the chart point goes down and into area D_4. The same, when the chart point meets the line $\phi = 0$ which means $\phi = 0$ and $\Psi < 0$, then the chart point goes left and into area D_2. Starting from this region, the phase point tends to be stable at E_4 or enters into area D_2 or area D_4.

In area D_4, the evolutionary characteristics of the two agents are $\phi > 0$ □ $\Psi > 0$ which means that the growth rate of agent dx_1/dt is greater than zero and the same to that of agent dx_2/dt. When the chart point meets the line $\Psi = 0$ which means $\phi > 0$ and $\Psi = 0$, then the chart point moves left, which cannot enter area D_3. The same, when the chart point meets the line $\phi = 0$ which means $\Psi > 0$ and $\phi = 0$, then the chart point moves up and cannot enter area D_1. Starting from this area, the phase point only tends to be stable at point E_4,

In summary, only if $\operatorname{sgn}(bc - ad), \operatorname{sgn}(a - c), \operatorname{sgn}(b - d)$ have the same symbols, the symbiotic evolutionary equilibrium point is $\boldsymbol{E}_4$, the supply side symbiosis system will be asymptotically stable at the point $\boldsymbol{E}_4$ regardless where the initial starting point starts.

III. Parameter Influence Analysis of Model on the Stability Point

The stability point E_4 is the coexistence equilibrium point of two agents, and the influence of the model parameters on the stability point is discussed according equation (1).

Equation (6) to (10) can be found according to the derivative of the formula $E_{4x} = \frac{Mac(b-d)}{bc-ad}$ by *M*, *a*, *b*, *c* and *d* respectively.

$$\partial E_{4x} / \partial M = \frac{ac(b-d)}{bc-ad} \tag{6}$$

$$\partial E_{4x} / \partial a = \frac{Mbc^2(b-d)}{(bc-ad)^2} \tag{7}$$

$$\partial E_{4x} / \partial b = -\frac{Macd(a-c)}{(bc-ad)^2} \tag{8}$$

$$\partial E_{4x} / \partial c = \frac{Ma^2d(d-b)}{(bc-ad)^2} \tag{9}$$

$$\partial E_{4x} / \partial d = \frac{Mabc(a-c)}{(bc-ad)^2} \tag{10}$$

It can be seen from the formula (6) that increase in the maximum volume of construction market accepted by the society will lead to the stable point moving right, which means the areas of green building increase. Where formula (7) shows that the direction of change is determined by the sign of $(b-d)$, which means an increase in unit area profit will lead to the system stable point moving right, namely the area of the green building increases. The contrary conclusion can be achieved from formula (9), which means an increase in unit area incentive cost will lead to the area decrease of the green building. Where formula (8) shows the direction of change is determined by the sign of $(a-c)$, which hints an increase in unit area profit without government incentives will lead to the system stable point moving left, namely the areas of green building decrease; the contrary conclusion cab be found from formula (10), which means that increasing of penalties because of developer's default will lead to an increase in the green building area.

In the same way, equation (11) to (15) can be respectively found according to the derivative of the formula $E_{4y} = \frac{Mbd(a-c)}{bc-ad}$ by *M*, *a*, *b*, *c* and *d* respectively.

$$\partial E_{4y} / \partial M = \frac{(a-c)bd}{bc-ad} \tag{11}$$

$$\partial E_{4y} / \partial a = \frac{Mbcd(b-d)}{(bc-ad)^2} \tag{12}$$

$$\partial E_{4y} / \partial b = -\frac{Mad^2(a-c)}{(bc-ad)^2} \tag{13}$$

$$\partial E_{4y} / \partial c = -\frac{Mabd(b-d)}{(bc-ad)^2} \tag{14}$$

$$\partial E_{4y} / \partial d = \frac{Mb^2c(a-c)}{(bc-ad)^2} \tag{15}$$

Under the condition that E_4 is stable point, it can be seen from the formula (11) that increase in the maximum volume of construction market accepted by society will lead to the stable point moving up, which means the numbers of government incentive increase. Where formula (12) shows that the direction of change is determined by the sign of $(b-d)$, which means that increase in unit area profit will lead to the system stable point moving up, namely the increase of government incentives. The contrary conclusion can be achieved from formula (14), which means an increase in unit area incentive cost will lead to the government incentives decrease. Where formula (13) shows the direction of change is determined by the sign of $(a-c)$, which hints an increase in unit area profit without government incentive will lead to the system stable point moving down, namely the decrease of government incentives; the contrary conclusion hints in formula (15), an increase of penalties will lead to an increase in the green building area.

IV. Conclusion

An evolutionary symbiosis model considering the carrying capacity dependent on green building supply side are established in this paper. On the basis of our analysis, the increase in the maximum volume of the construction market accepted by the society will lead to both the areas of green buildings and the incentives of the government increase at the same time. Payoff dependent and fixed total population is the dominant assumption of evolutionary game theory in the past decades. But in the ecological and social contexts, this is not always right; there are many other factors affecting the evolutionary process, such as density limitation. In this paper, a simple evolutionary model considered the payoff and density limitation have been studied. This extension of symbiosis theory seems entirely natural. In particular, it can be seen as an implementation of the carrying capacity into the symbiosis dynamics. The stochastic and spatial evolutionary games considering capacity limitation will be investigated in the future work. Here a deterministic, non-spatial symbiotic system has been explored, and some interesting similarities with the traditional replicator equation have been found.

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