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Study on Green Transformation Evolution of Construction Enterprises Based on Dissemination and Complex Network Game

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Abstract: The green transformation of construction enterprises (GTCEs) is an important way to develop green buildings and realize the goal of "double carbon". The GTCEs is not only influenced by the internal characteristics of the group but also influenced by the governmental orientation and the pull of the consumer groups. This paper simultaneously considers the heterogeneity of consumer groups and construction enterprise groups, coupling the improved SIR dissemination model, complex network model, and evolutionary game model to describe the dynamic interaction process between construction enterprise groups, government, and consumer groups and to explore the evolution law of GTCEs. The results show that (1) Appropriately increase in green R&D investment by construction enterprises for higher returns, the government's subsidy and penalty policies and a higher carbon trading price have a positive effect on the GTCEs; (2) a positive social climate, along with the government's publicity and education, the higher technology level of construction enterprises, and the higher green cognition and lower risk perception level of consumers will strongly promote the GTCEs; and (3) a steady development of the GTCEs is guaranteed by the enterprises' own inputs and the government's joint measures on both the supply and demand sides. The conclusions of this study can be used as a reference for the government to formulate policies and for the green transformation and development of construction enterprises.

Keywords: construction enterprises; green transformation; dissemination model; complex network; evolutionary game

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1. Introduction

As global warming, melting glaciers, and other environmental problems arise, carbon emissions have become a focus of attention around the world. Data from the report published by the UN Environment Programme shows that the construction industry is now the largest emitter of greenhouse gases, accounting for 37% of global carbon emissions and consuming 34% of the world's energy demand [1]. China is the largest carbon emitter in the construction sector [2]. Data from the "*China Building Energy Consumption Annual Research Report 2023*" show that the energy consumption of the whole process of the construction sector in 2021 occupies 44.7% of China's total energy consumption, and the carbon emissions throughout the whole process are about 44.1% of the country's total carbon emissions [3]. Therefore, it is crucial to realize energy-saving and emission-reduction measures in the construction sector. With the introduction of a sustainable development strategy and 'dual-carbon' goals, the construction sector has been forced to change its way of development; as one of the measures considered to significantly reduce building energy consumption and carbon emissions, green buildings have received much attention by researchers and construction enterprises [4]. Compared to traditional buildings, green buildings reduce 30–50%, 35%, 40%, and 60% energy consumption, carbon dioxide emissions (CO_2), water use, and waste output, respectively [5]. In addition, with the promulgation of the revised "Assessment Standard for Green Buildings" (GB/T50378-2019) [6], the connotation of green building has been expanded, the requirements of green building have been improved, and the pursuit of 'high-quality building' has been clarified. Therefore, in the context of increasingly severe global resource and environmental problems, it is necessary to accelerate the GTCEs and develop high-quality green buildings in order to achieve the 'dual-carbon' goal and promote the process of sustainable development.

The high-quality development of green buildings cannot be separated from the joint participation of the government, construction enterprises, and consumers. The construction enterprise group is the supply side of green buildings and one of the main bodies for developing green buildings; thus, analyzing the green transformation evolution of the construction enterprise group is an important issue for the development of green buildings. The group of construction enterprise is a heterogeneous group, and the individual enterprises differ greatly in terms of product type, scale, R&D capability, etc.; they have different options when faced with different decisions, so the evolution of the green transformation of the construction enterprises group is affected by the individual characteristics of the enterprises and interactions within the group. Shi et al. analyzed the diffusion of green technology among enterprises using an agent-based evolution model, taking into account the heterogeneity of individual enterprises and interactions within the group [7]. In addition, as a policy maker and regulator of the institutional environment, the government can formulate promotional policies and design incentive mechanisms to guide the development of green transformation of the construction enterprise groups [8]. At the same time, as the demand side of green buildings, the consumption intention of a consumer (CIC) will also affect the choice of green behavioral strategies of construction enterprises [9]. Moreover, consumer groups are also heterogeneous, which means that there are differences among individuals within the group, i.e., differences in rationality, information acquisition, and processing ability of individuals; thus, it leads to the fact that people will be influenced by cognitive limitations, emotional factors, and external environment when making decisions. As an important theory in the study of consumer decision-making and behavior, the theory of planned behavior [10] suggests that an individual's intention influences an individual's behavior and that the main influences on an individual's intention are attitudes and perceived behaviors, etc. In addition, there is a herd effect in consumer groups, i.e., the behavior of the group can influence the norms of individual consumers and thus affect individual decision-making [11]. Therefore, the dynamics of CICs are also influenced by individual consumer characteristics and intra-group interactions. Rezai et al. used a structured questionnaire to interview consumers and a correlation analysis model to analyze the influence of individual consumer behavior and social relationships (friends and colleagues) on consumers' green consumption intentions [12].

In the existing research, the dynamic change process of green behavior strategy of construction enterprises is mainly analyzed based on the evolutionary game theory, with less consideration of the heterogeneity of the construction enterprise group and the interaction between enterprises within the group. The consumer groups are analyzed based on the assumption of being homogeneous, and previous studies have rarely considered the mechanisms by which different factors that affect changes in consumer intention operate within consumer groups, as well as the impact of their dynamic changes on the green behavior strategies of construction enterprises. Although some of the results analyze the evolution of green transformation in the group of construction enterprises [13], as well as the evolution of consumer intention in the group of consumers [14,15], they analyze a single group and do not analyze the interaction between the two groups. Therefore, it is important to take into account the heterogeneity of the construction enterprise group and the consumer group, and to consider the interactive influence of the government and the consumer group on the construction enterprise group in order to analyze the law of GTCEs.

The main contributions of this study are: Firstly, in the research framework, this paper considers the heterogeneity of supply-side and demand-side groups as well as the interaction between the two groups at the same time, and couples the evolutionary game model of complex networks with the improved SIR dissemination model to describe the characteristics of the supply-side and demand-side groups of green buildings and their dynamic interaction process, which is more complex but more in line with the actual situation. Secondly, the dynamic process of the groups under the action of different influencing factors and the interaction law among the different groups are investigated so as to provide references for the government to formulate policy and the development of GTCEs.

2. Literature Review

2.1. Development Status of GTCEs

The development of green building in China is phased, and some scholars have summarized the development of green building in China into three phases, i.e., the initial phase, the rapid development phase, and the further development phase [16]. With the gradual deepening of the development, some progress has been made in green building in China. According to the Ministry of Housing and Urban-Rural Development, data show that, as of 2019, China's total building area reached 66.4 billion m^2, the country's cumulative green building area reached 5 billion m^2, including 20,000 green building labeling projects, with an area of about 2 billion square meters; as of 2023, the national green building area will exceed 10 billion m^2, and the number of green building label projects will reach 27,000 [17]. While green buildings have made some progress, they are also facing new problems, and in the newly revised "Assessment Standard for Green Buildings" (GB/T50378-2019) [6], higher requirements have been set for green buildings to pursue a higher quality of green building. Therefore, there are still some problems in its development: the green building market is not mature, green residential buildings are not widely used, and the number of high-quality buildings is still in short supply [18]. Moreover, carbon emissions from the construction industry remain high [3], and with the further development of urbanization, there is still an urgency to promote the comprehensive and high-quality development of green buildings under the requirements of the 'dual-carbon' strategic goal.

2.2. Factors Influencing Green Behavior Strategies of Construction Enterprises

Factors affecting the choice of green behavioral strategies for construction enterprises can be divided into internal and external factors. Firstly, among the internal factors, enterprises have different attitudes towards green buildings due to their own cost investment and benefit situations. Hu et al. found that increased technological investment by construction enterprises had a significant impact on the development of green buildings [19]; enhancing the green incremental benefits of construction enterprises can effectively promote green building development [20]. And enterprises with sufficient capital, strong innovation ability, and high social responsibility will be more likely to choose green building projects [9].

Secondly, the external factors affecting the choice of enterprises' green behavior strategies include the government policy environment, consumer demand, etc.

The development of green buildings cannot be separated from the guidance of the government, which promotes and guides the development of green buildings through the promulgation of policies and regulations, and these policies are grouped into five categories, including direction-based, technical support, financial support, service-based, and regulation-based policies [16]. Financial subsidies for construction enterprises can be an effective way to promote the development of green buildings [21]; unilateral penalties for non-low-carbon enterprises can be an effective incentive for non-low-carbon enterprises to make a green transformation [7]; and combining government incentives and penalties can promote the adoption of green technologies by enterprises [22]. Some scholars, through forecasting China's carbon emissions and the carbon emissions of the construction sector, have found that a low-carbon development pathway is conducive to achieving the "dual-carbon" goals [23–25]. Therefore, carbon reduction in the construction sector is of great significance. Carbon reduction strategies also have an impact on the behavior and decision-making of construction enterprises, with carbon tax being an effective measure in promoting the development of green buildings [26], while carbon trading in the construction sector has a positive significance for improvements in energy efficiency and ecology [27]. Tianjin takes the lead in bringing construction carbon emissions into the carbon trading market [28]. Moreover, scholars have studied the carbon trading mechanism for public buildings [29], green buildings [30], residential buildings [31], etc. Appropriately increasing the carbon price will be conducive to the green behavior of construction enterprises [32], and a higher carbon market participation rate has an additional promoting effect on the construction enterprises adopting green behavior [33].

Regarding consumers as the demand side of construction products, their green consumption demand will pull the GTCEs. Indeed, the diffusion of green products is driven by the demand of the consumer side; increasing green consumption demand promotes the diffusion of low-carbon technology [34]. Certain behaviors and measures targeting consumers can also have an impact on the spread of green products, increasing green consumption vouchers on the consumer side, with publicity and education having a positive impact on the diffusion of green products [35], while the level of consumers' environmental awareness affects the development of low-carbon enterprises [36]. Most of the existing studies treat consumers as a homogeneous group, but in fact, the CIC is influenced by a variety of factors [12], such as policy [37], green knowledge [38], building quality [39], living habits [40], economic costs [41], income [42], technology [43], consumer environmental awareness [44], social interaction [45], etc.

2.3. Application of Dissemination Models

Dissemination models are also known as epidemic models, and according to the type of epidemic, they are divided into the SI model [46], SIS model [47], SIR model [48], SIRS model [49], SEIR model [50], and other models. The epidemic model was initially only applied to the analysis of the dissemination of disease in the medical field. It has attracted attention due to its ability to vividly and accurately describe the mechanism of transmission and has been widely applied in various research fields; for example, using the SIS model to analyze the co-evolution of transportation behavior and disease dissemination in the context of information diffusion mechanism [51], using the EP-SIS and EO-SIS models to guide netizens' emotions after emergencies to achieve social stability [52], using an improved SIR model to explore the role of different influential factors in promoting green behavior among contractors [53], using improved SIR and SEIR models to study the green retrofit of traditional residential complexes with resident group participation [14,15], while risk propagation in the sharing of project portfolio resources was investigated using an improved SIR model [54], etc. The epidemic model can classify people according to the different infection statuses, and at the same time, with the spread of disease infection, the population status will change. Similar to the epidemic model, the CIC is also different, with the dissemination of green building information under the influence of different factors, which leads to a conversion of the state of the CIC. In addition, the conversion state of the CIC under the influence of different factors is similar to the mechanism of state conversion that results from viral infection of the population in the epidemic model. Firstly, the nodes in both the epidemic model and the consumer group are human beings, and secondly, state conversions in the epidemic model are related to the rate of infection, whereas state conversions in the CIC are related to the dissemination of information and influencing factors. Finally, no group exists on its own and is integrated with other groups and the social environment. Therefore, from the above description and analysis, it can be concluded that an improved epidemic model can be used to describe the dynamic process of the conversion of the CIC.

2.4. Complex Networks and Evolutionary Game Models

Evolutionary game theory is developed on the basis of traditional game theory and biological evolution theory [55], which focuses on the interaction between individuals and how decision-makers make strategic adjustments in the dynamic process, providing a scientific theoretical framework for studying the dynamic process of the development of things [56,57]. While group behavior is a unified reflection of individual behavior at the macro level, how group behavior interacts and evolves has been a hot topic of research in recent years. In reality, many groups have a certain structure and function, and the evolutionary game in these groups is closely related to their structure [58,59]. Complex networks can effectively describe the structure and function of complex systems, where nodes in the network represent individuals in a group, and the connections and interactions between individuals are described by connecting edges. Therefore, the use of micro-mechanisms to reflect the phenomena at the macro level of the system or group is an effective approach, and in enterprise groups with a certain relational structure, the structure and functioning of complex networks can be used to characterize the links between individuals, and thus to study the diffusion and evolution of the group's behavior [60]. For the construction enterprise group, the enterprise group has heterogeneity, and the group has a certain structure and function, and there is a connection between the enterprises, which will consider its own situation and the enterprises connected to it to make choices in the face of decision-making. Therefore, using the method of combining complex networks and evolutionary games to study the evolution of groups with structure and function has certain theoretical advantages [61].

The approach of combining complex networks with evolutionary games has been widely used in the field of low-carbon and green innovation. Wang et al. simulated the diffusion of low-carbon products among enterprises with different strategies by constructing an evolutionary game model based on complex networks [36]. Li et al. studied the impact of different government policies on electric vehicle adoption based on an evolutionary game model with small-world networks of different scales [62]. Yang et al. established a complex network-based evolutionary game model to analyze the impacts of different policies adopted by the government on the demand side and the supply side on the diffusion of green products [35]. Based on the small-world network model, Liu et al. explored the evolutionary game law of low-carbon technology diffusion of competing enterprises under the carbon trading mechanism [63]. The above pieces of literature show that the combination of complex networks and evolutionary games is highly adaptable to the study of strategy diffusion of green behavior among individuals.

2.5. Summary

From the above, it can be seen that with the proposal of the sustainable development strategy and 'dual-carbon' goal, the requirements for green buildings are growing higher and higher, and it is necessary to develop high-quality green buildings. As the supply side of green buildings, construction enterprises do not exist independently, and their green behavior strategies are influenced by other construction enterprises, government measures, and the CIC. Consumer groups are heterogeneous, and their green consumption intention is affected by a variety of factors. Considering the influencing factors affecting the CIC, an improved SIR dissemination model is constructed on the demand side to describe the dynamic process of consumers' consumption intention transformation. Meanwhile, a complex network-based evolutionary game model is constructed on the supply side under the comprehensive consideration of the different influencing factors and the structure of the group of construction enterprises. Finally, considering the interaction between the construction enterprise group and the consumer group, the above two models are coupled to analyze the impact of the dynamic changes in the government, the construction enterprise behavior, and the CIC on the green behavior strategy of the construction enterprise, so as to provide a theoretical basis for the promotion of the GTCEs as well as the high-quality development of a green building.

3. Model

3.1. Analytic Framework

The GTCEs are the result of the joint action of the government, construction enterprises, and consumers. The green transformation decisions of construction enterprises are impacted by their own conditions and the strategies of other construction enterprises in the group. An enterprise's own factors, such as R&D investment and benefits, government measures, such as subsidies, penalties, and carbon trading, as well as changes in demand, all affect the strategic choices of construction enterprises. And here, an evolutionary game model is used to describe the dynamic strategic choices of construction enterprises, and a complex network is utilized to describe the process of interactions within the group of construction enterprises. Government measures for consumers, such as publicity and education, and enterprise factors, such as the technology level of the enterprise, as well as consumers' green cognition and risk perception, affect the CIC, which, in turn, affects the demand for buildings. Here, an improved SIR model is used to describe the dynamic process of the conversion in the CIC. An analysis framework is shown in Figure 1. (Note: the arrows inside the box indicate a dynamic transformation of the strategies of construction enterprises on the supply side and the state of the CIC on the demand side, while the arrows outside the box indicate the influencing factors generated by different subjects' behaviors).

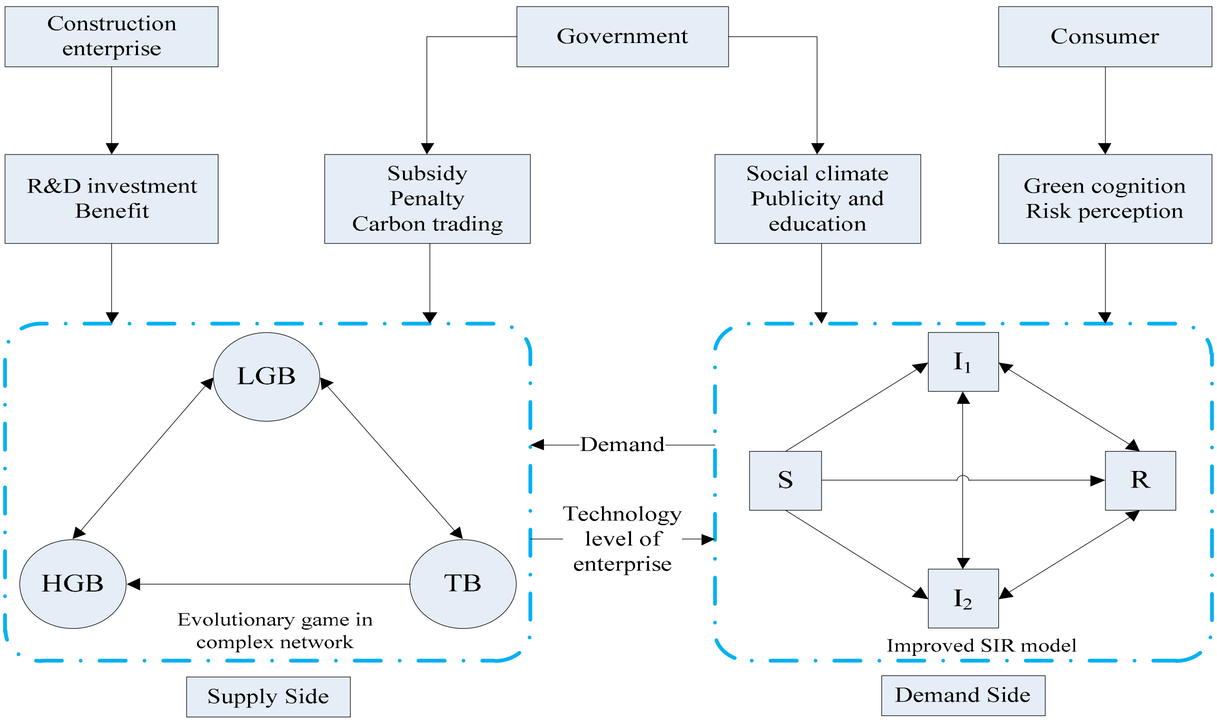

Figure 1. Analytic framework. (Note: HGB: high-quality green building; LGB: low-quality green building; TB: traditional building; S: potential consumer; I_1: high-quality green building consumer; I_2: low-quality green building consumer; R: traditional building consumer).

3.2. Improved Dissemination Model

The consumer group includes potential consumers, green building consumers, and traditional building consumers. According to the differences in the intention and cognitive level of green building consumers, the dissemination population can be divided into two types: high-quality green building consumers and low-quality green building consumers, and they can be transformed into each other. Considering the diversity and flexibility of consumer intentions, the immune group, i.e., traditional building consumers, can be converted to green building consumers according to their own performance and the influence of internal and external factors, so the traditional SIR model needs to be improved to describe the conversion of the CIC.

3.2.1. Basic Assumptions

Assumption 1: Different consumers have different consumption intentions, and given the large number of consumers, it is not possible to characterize the individuality of each consumer in the study. Consumers with the same intention to consume are divided into one category, and the consumer groups are divided into potential consumers (S), high-quality green consumers (I_1), low-quality green consumers (I_2), and traditional consumers (R). Consumers in each category form a subgroup, and consumers in each subgroup are homogeneous, and consumers in different categories are different. Considering the factors affecting consumers' intentions to consume, for consumers in the same group with the same intention to consume, the influencing factors are the same, and their probability of conversion is the same, while for consumers in different categories with different intentions to consume, their probability of conversion is different under the influence of different influencing factors. During the evolutionary period, the total number of consumers remains constant, $S + I_1 + I_2 + R = n$.

Assumption 2: The dissemination and conversion of the CIC are jointly influenced by internal and external factors. Drawing on relevant research [12,39,64–68], internal factors include the level of consumers' environmental awareness (o), green cognition (g), and risk perception (d); external factors include the social climate level (h), the level of government publicity and education (q), and the technology level of the construction enterprises (l).

Assumption 3: At moment t, the probability that potential consumers S become high-quality green consumers I_1, influenced by their own level of environmental awareness is $o\beta_1$, and the probability of becoming low-quality green consumers I_2 is $(1 - o)\beta_2$. Additionally, β_1, β_2 are the success rates of potential consumers S being converted into high-quality I_1 and low-quality green consumers I_2, $\beta_1 > \beta_2$, indicates that consumers have a higher success rate of being converted by positive messages compared to those that are negative. The probability of conversion of potential consumers S into traditional consumers R, influenced by their level of environmental awareness and the social climate level is $(1 - o)(1 - h)$.

Assumption 4: At moment t, the probability of conversion of high-quality consumers I_1 into low-quality green consumers I_2, influenced by their own level of green cognition g and risk perception d, is $(1 - g)d$. Additionally, the probability of being converted into traditional consumers R, influenced by the level of government publicity and education q, and the level of social climate h, is $(1 - h)(1 - q)$.

Assumption 5: At moment t, the probability of conversion of low-quality consumers I_2 to high-quality green consumers I_1, influenced by their level of green cognition g and technology level of the construction enterprise l, is gl. Also, the probability of conversion into traditional consumers R, influenced by their level of green cognition g and risk perception d, is $(1 - g)d$.

Assumption 6: At moment t, the probability of conversion of traditional consumers R into high-quality green consumers I_1, influenced by social climate level h and technology level of the construction enterprise l, is hl, while the probability of conversion into low-quality green consumers I_2 is $(1 - h)(1 - q)$.

Assumption 7: At moment t, the quantities of potential consumers S, high-quality green consumers I_1, low-quality green consumers I_2, and traditional consumers R in the consumer group are $S(t)$, $I_1(t)$, $I_2(t)$, and $R(t)$, where $S(t) + I_1(t) + I_2(t) + R(t) = n$.

3.2.2. Model Construction

The improved SIR dissemination model is shown in Figure 2, which represents the state conversion relationship between individuals with different consumption intentions in a consumer group and connects different individuals into a connected system through mutual contact.

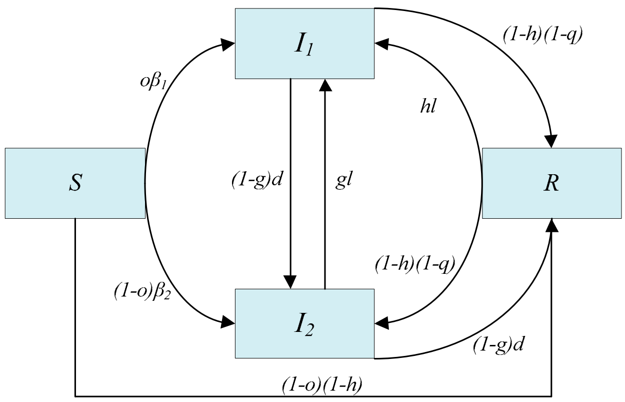

Figure 2. The improved dissemination model.

According to the above assumptions, the dynamic equations of state conversion of consumer consumption intentions are established as shown below:

$$\begin{cases} \frac{dS}{dt} = -o\beta_1 S(t) - (1-o)\beta_2 S(t) - (1-o)(1-h)S(t) \\ \frac{dI_1}{dt} = o\beta_1 S(t) + glI_2(t) + hlR(t) - (1-g)dI_1(t) - (1-h)(1-q)I_1(t) \\ \frac{dI_2}{dt} = (1-o)\beta_2 S(t) + (1-g)dI_1(t) + (1-h)(1-q)R(t) - glI_2(t) - (1-g)dI_2(t) \\ \frac{dR}{dt} = (1-o)(1-h)S(t) + (1-h)(1-q)I_1(t) + (1-g)dI_2(t) - hlR(t) - (1-h)(1-q)R(t) \end{cases} \quad (1)$$

3.3. Construction Enterprises Profits

Construction enterprises include three strategies: constructing a high-quality green building (HGB), constructing a low-quality green building (LGB), and constructing a traditional building (TB). At moment t, the number of enterprises with three different strategies are $HGB(t)$, $LGB(t)$, and $TB(t)$, and satisfy $HGB(t) + LGB(t) + TB(t) = N$, and their proportions to the total scale of the group are $x = \frac{HGB(t)}{N}$, $y = \frac{LGB(t)}{N}$, and $z = \frac{TB(t)}{N}$, respectively, $0 \leq x, y, z \leq 1$. Different strategic choices of construction enterprises result in different benefits.

3.3.1. Basic Profit

The basic profit consists of its net profit per unit area of building and the corresponding demand quantity. First, in this model, the consumer demand is assumed that the corresponding market demand is evenly distributed among the corresponding groups of construction enterprises, and the specific demand distribution can be calculated by Equations (2)–(4):

$$q_{HGB} = \frac{I_1(t)}{HGB(t)} \quad (2)$$

$$q_{LGB} = \frac{I_2(t)}{LGB(t)} \quad (3)$$

$$q_{TB} = \frac{R(t)}{TB(t)} \quad (4)$$

where q_{HGB}, q_{LGB}, and q_{TB} represent the market demand for selecting HGB, LGB, and TB, respectively.

Therefore, the basic profits of the construction enterprises with the above three strategies can be calculated by Equations (5)–(7):

$$U_{HGB} = (R_1 - C)q_{HGB} = (R_1 - C)\frac{I_1(t)}{HGB(t)} \quad (5)$$

$$U_{LGB} = R_2 q_{LGB} = R_2 \frac{I_2(t)}{LGB(t)} \quad (6)$$

$$U_{TB} = R_3 q_{TB} = R_3 \frac{R(t)}{TB(t)} \tag{7}$$

Here, it is assumed that the benefits per unit area of HGB, LGB, and TB are R_1, R_2, and R_3, respectively, and C is the R&D investment per unit area of HGB, where $R_1 > R_2 > R_3$.

3.3.2. Construction Enterprise Payoff Under Government Policy

Assuming the government subsidy per unit area of building received by HGB is b, then its financial subsidy is shown as follows:

$$S = bq_{HGB} = b\frac{I_1(t)}{HGB(t)} \tag{8}$$

The penalties per unit area of TB and LGB are h_1 and h_2, respectively, then the penalties are shown as follows:

$$G_1 = h_1 q_{TB} = h_1 \frac{R(t)}{TB(t)} \tag{9}$$

$$G_2 = h_2 q_{LGB} = h_2 \frac{I_2(t)}{LGB(t)} \tag{10}$$

3.3.3. Carbon Trading

For each unit area of building, a certain amount of carbon quota e_0 is allocated, and the carbon emissions per unit area of building for HGB, LGB, and TB are e_1, e_2, and e_3, where $0 < e_1 < e_0 < e_2 < e_3$, so that the carbon price in the carbon trading market is set to be p, and the benefits of the construction enterprises of the above three strategies in the carbon trading market can be obtained by Equations (11)–(13):

$$F_{HGB} = p(e_0 - e_1)q_{HGB} = p(e_0 - e_1)\frac{I_1(t)}{HGB(t)} \tag{11}$$

$$F_{LGB} = p(e_0 - e_2)q_{LGB} = p(e_0 - e_2)\frac{I_2(t)}{LGB(t)} \tag{12}$$

$$F_{TB} = p(e_0 - e_3)q_{TB} = p(e_0 - e_3)\frac{R(t)}{TB(t)} \tag{13}$$

Given that decision-makers in enterprises generally choose strategies based on their perceived gains and losses rather than actual ones, it means that for individuals in risky decision-making, their decision-making is not completely rational and is influenced by psychological preferences, i.e., when faced with equal gains and losses, individuals' psychological perceptions are asymmetric and are more reluctant to suffer a loss than to gain an equal gain, i.e., they exhibit more sensitivity to losses [69]. Therefore, the prospect theory, expressed as Equation (14), is used to describe the psychology towards gains and losses.

$$\prod(E) = \begin{cases} E^{\alpha} & E > 0 \\ -\beta(-E)^{\gamma} & otherwise \end{cases} \tag{14}$$

The E represents the absolute value of a gain or loss. Among them, α, γ, $(0 < \alpha, \gamma < 1)$ denote the risk preference coefficients; a larger value of α within the gain region implies that decision-makers prefer to be risk-seeking towards gains, while a larger value of γ within the loss region implies that a decision-maker is risk-averse to loss, and β $(\beta \geq 1)$ is the loss aversion coefficient. Therefore, based on the above analysis, the final payoff regarding the three strategies of construction enterprises, i.e., choosing high-quality green buildings, low-quality green buildings, and traditional buildings, can be expressed by Equations (15)–(17):

$$W_{HGB} = U_{HGB} + \prod(S) + \prod(F_{HGB}) \tag{15}$$

$$W_{LGB} = U_{LGB} + \prod(G_2) + \prod(F_{LGB}) \tag{16}$$

$$W_{TB} = U_{TB} + \prod(G_1) + \prod(F_{TB}) \quad (17)$$

3.4. Evolutionary Mechanism for GTCEs in the Complex Network

The green transformation evolution mechanism of construction enterprises in the complex network is shown in Figure 3.

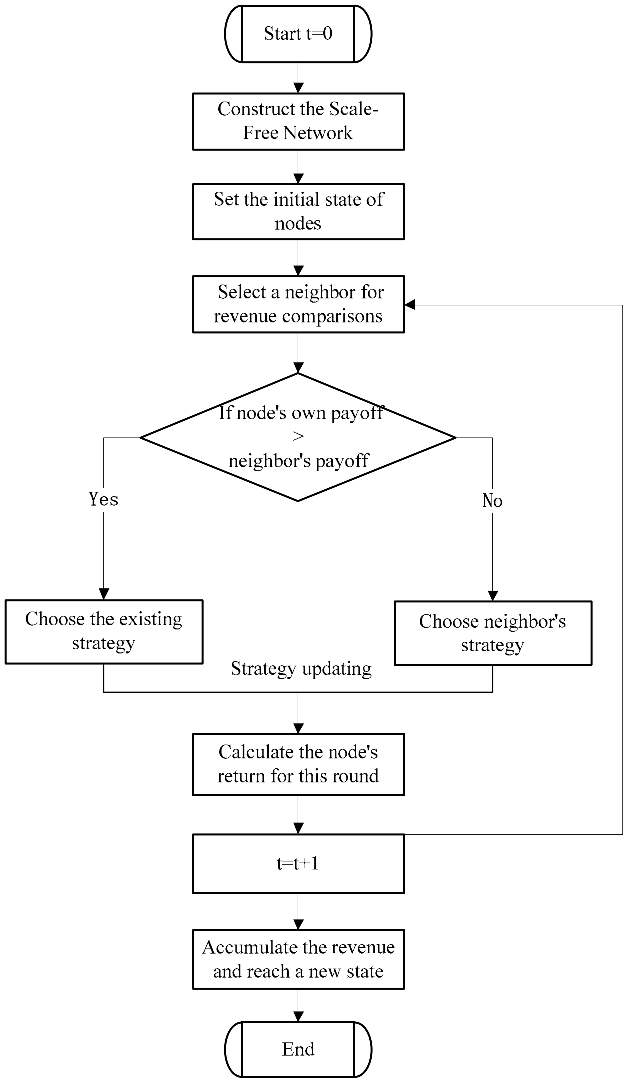

Figure 3. The evolutionary mechanism within groups of construction enterprises.

(1) Complex networks are constructed. Construction enterprises connect with each other through social networks, and green building behaviors are disseminated in the network. In the complex network, each node represents an individual construction enterprise, and the connecting edges represent the connections and interactions between construction enterprises. Given the structure of the group of construction enterprises and the heterogeneity within the group, the larger and more active enterprises in the construction sector will possess more links with other enterprises, so the BA scale-free networks [70] are used to describe the structure and links within the group of construction enterprises. The structure of a scale-free network is denoted by $G = (N_{\mathrm{i}}, \Omega_i | i \in N)$, where each node of i represents a construction enterprise within the group, and Ω_i represents all the neighbors of the node i, $\Omega_i = (j | j \in N_i)$. A simple overview of constructing a scale-free network is shown below:

(1) Growth: the initial number of nodes in the network is m_0, and each time a node is added, the number of edges added is m, which satisfies $m < m_0$; here, let m_0 = 5 and m = 3.

(2) Priority connection: the probability of each new node connecting to an existing node is calculated by Equation (18):

$$\omega_i = \frac{k_i}{\sum_j k_j} \tag{18}$$

where k_i refers to the degree of a node, which indicates the number of edges connected to that node or the number of its neighboring nodes.

(2) The initial policy choices of the construction enterprises are randomly assigned to the network's nodes.

(3) Revenue comparison. In each round of the game, an individual randomly selects a neighbor for cumulative gain comparison, learns its neighbor's strategy with a certain probability according to the Fermi evolution rule Equation (19), and enters the next round. In this study, if an individual's strategy is HGB, it will not be updated to a TB strategy due to the factors of prior investment and large conversion costs when comparing the gains of the TB enterprises and learning to change the strategy to enter the next round:

$$P_{i-j} = \frac{1}{1 + \exp[(\pi_i - \pi_j)/k]} \tag{19}$$

where π_i and π_j refer to the cumulative returns, and here, k represents the noise factor, which can be understood as an individual making irrational choices, indicating that the construction enterprise is a finite rational individual who does not have access to all the information when making decisions; the closer it is to 0, the more rational the individual is, and it was denoted to be 0.1 [71].

(4) Proceed to the next round of gaming until the end.

This part describes the process of model construction, which mainly includes the improved dissemination model and the evolutionary game model based on a complex network. Considering the characteristics of the supply-side and demand-side groups, the complex network-based evolutionary game model and the improved dissemination model are constructed in the supply side and demand side, respectively, and the improved SIR dissemination model in the demand side and the complex network-based evolutionary game model in the supply side are coupled with each other in order to comprehensively explore the dynamic process of the evolution of the green transformation in the group of construction enterprises by taking the revenue as a link.

4. Numerical Simulation Results

According to the data released by the National Bureau of Statistics in September 2022, there are about 10,000 top-level construction enterprises. We set the size of the construction enterprises to N = 10,000, and the proportions of high-quality green construction enterprises, low-quality green construction enterprises, and traditional construction enterprises in the initial state group are x = 0.1, y = 0.2, and z = 0.7, respectively. Referring to studies [30,72], the initial values of the parameters of the building per unit area are as follows: R_1 = 650, R_2 = 550, R_3 = 500, C = 40, b = 50, e_0 = 0.15, e_1 = 0.08, e_2 = 0.15, e_3 = 0.20, p = 50, h_1 = 150, and h_2 = 75. According to research [73], there are 2,100,000 consumers in China, of which the proportion of green consumers is 0.1, so let n = 2,100,000, $S(0)$ = 147,000, $I_1(0)$ = 105,000, $I_2(0)$ = 105,000, and $R(0)$ = 4,200,000. Referring to study [69], we set $\alpha = \gamma$ = 0.89 and β = 2.25. The remaining parameters are: o = 0.5, h = 0.5, g = 0.5, l = 0.5, d = 0.5, q = 0.5, β_1 = 0.5, and β_2 = 0.3. This study used Matlab R2020b software for numerical simulation.

The impacts of government behavior, market factors, enterprises' own factors, and consumer factors on the GTCEs are discussed separately below.

4.1. The Impact of Government Behavior on the GTCEs

4.1.1. Impact of Governmental Penalty

The values of government penalties h_1 and h_2 are 0, 75, 150, 300, and 450, respectively, and the evolution of the group of construction enterprises is shown in Figures 4 and 5.

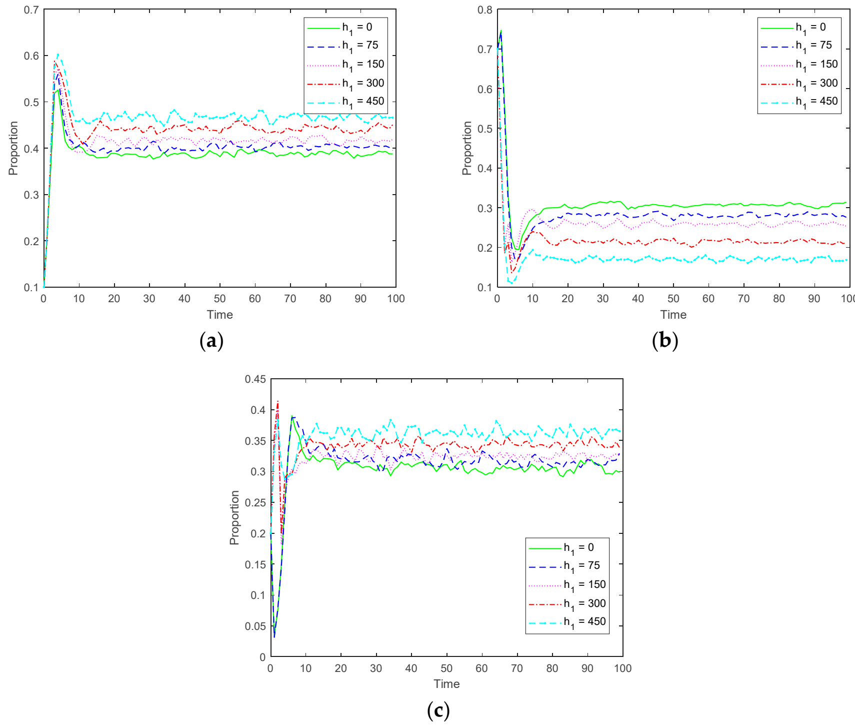

Figure 4. Impact of governmental penalties h_1: (**a**) high-quality green building enterprises; (**b**) traditional building enterprises; (**c**) low-quality green building enterprises.

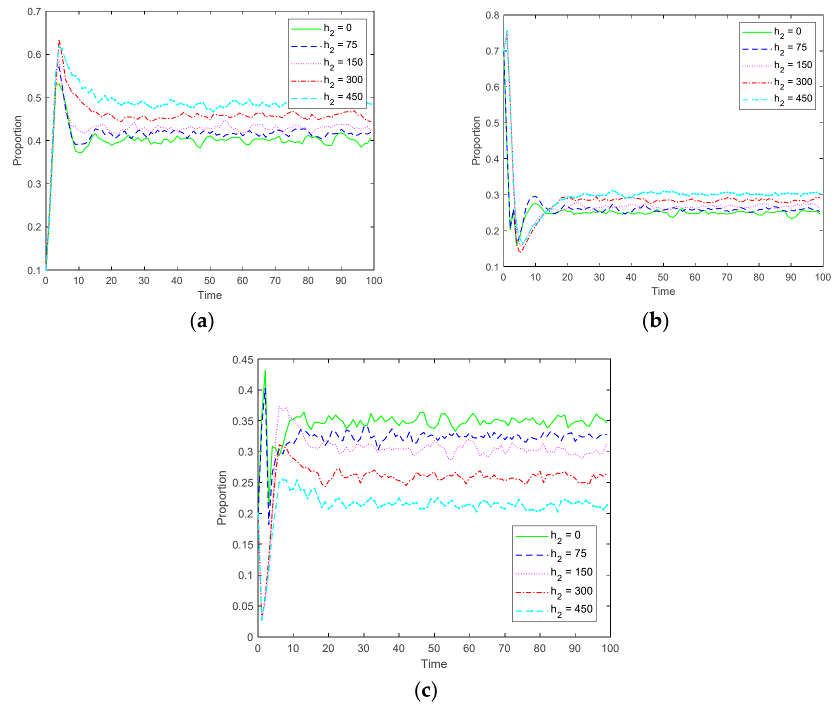

Figure 5. Impact of governmental penalties h_2: (**a**) high-quality green building enterprises; (**b**) traditional building enterprises; (**c**) low-quality green building enterprises.

As can be seen from the above simulation results, as the government increases the penalties for non-high-quality construction enterprises, respectively, the scales of the unpunished enterprises all increase. Both penalties and subsidies have asymmetric characteristics; compared to unilateral subsidy policies, construction enterprises are more sensitive to losses than to profits. The incentives for HGB enterprises are roughly the same for both types of penalties, and an increase in penalties for TB enterprises would be more conducive to energy efficiency and enterprise transformation in the construction sector than an increase in penalties for LGB enterprises only. Therefore, based on the above analysis, when the government formulates the corresponding punitive policies, it can consider differentiating between the LGB enterprises and TB enterprises in terms of certification so as to better utilize the government's regulatory role.

4.1.2. Impact of the Level of Government Publicity and Education

The level of government publicity and education q takes the values of 0.3, 0.5, 0.7, and 0.9, respectively, and the evolution of the group of construction enterprises is shown in Figure 6.

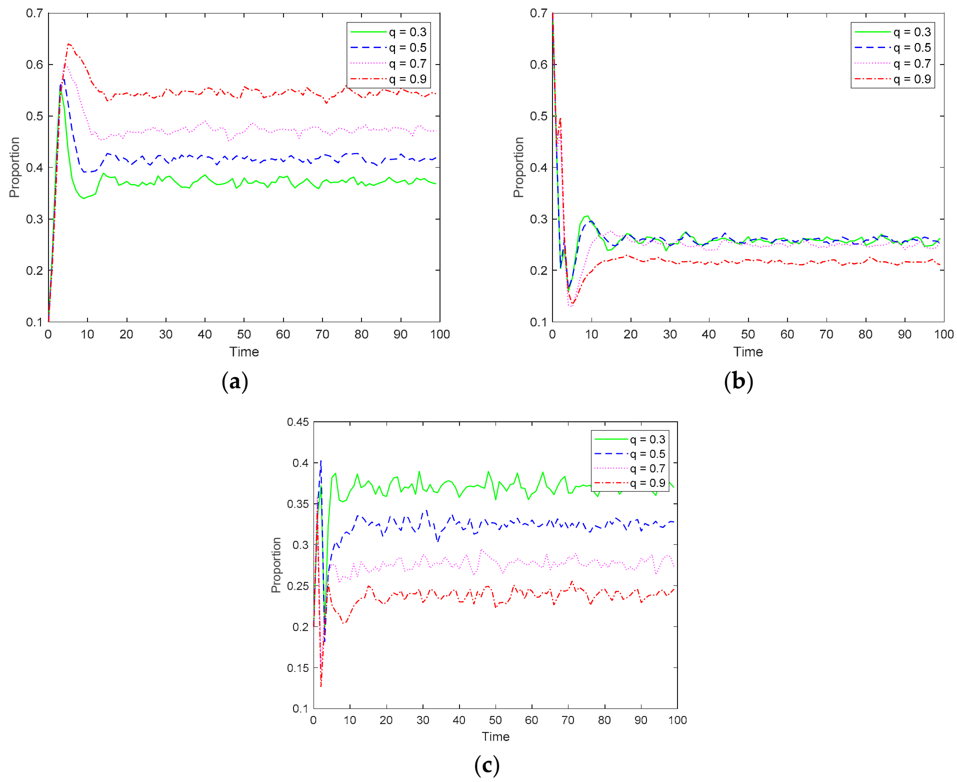

Figure 6. Impact of the level of government publicity and education q: (**a**) high-quality green building enterprises; (**b**) traditional building enterprises; (**c**) low-quality green building enterprises.

It can be seen that when the government improves the level of publicity and education for consumers, the scale of HGB enterprises increases, and the scale of TB enterprises and LGB enterprises keeps decreasing. According to the consumer intention dissemination model, when the level of government publicity and education is increasing, the concept of green building is deeply rooted in people's hearts, which makes the probability of high-quality green consumers converting into traditional green consumers decrease and the probability of traditional consumers converting into low-quality green consumers decrease, therefore, the scale of high-quality green consumers is increasing, which leads to the number of HGB enterprises is also increasing. From Figure 6b, the scale of TB enterprises only changes more significantly when the government's level of publicity and education is relatively high, so the government should strengthen the publicity and education of consumers so that consumers can understand and accept the green building from the ideological point of view.

In addition, when government subsidies are implemented, the scale of HGB enterprises increases with the increase in subsidies, while the scale of TB enterprises and LGB enterprises decreases with the increase in subsidies; at the same time, lower subsidies have a smaller role in promoting the development of HGBs, and the sensitivity of HGB enterprises to the subsidies decreases with the increase in subsidies, and these regularities are in line with the conclusions of the study [34], and will not be discussed in detail here.

4.2. The Impact of Market Factors on the GTCEs

4.2.1. Impact of Social Climate Level

The social climate level h is taken as 0.3, 0.5, 0.7, and 0.9, respectively, and the evolution of the group of construction enterprises is shown in Figure 7.

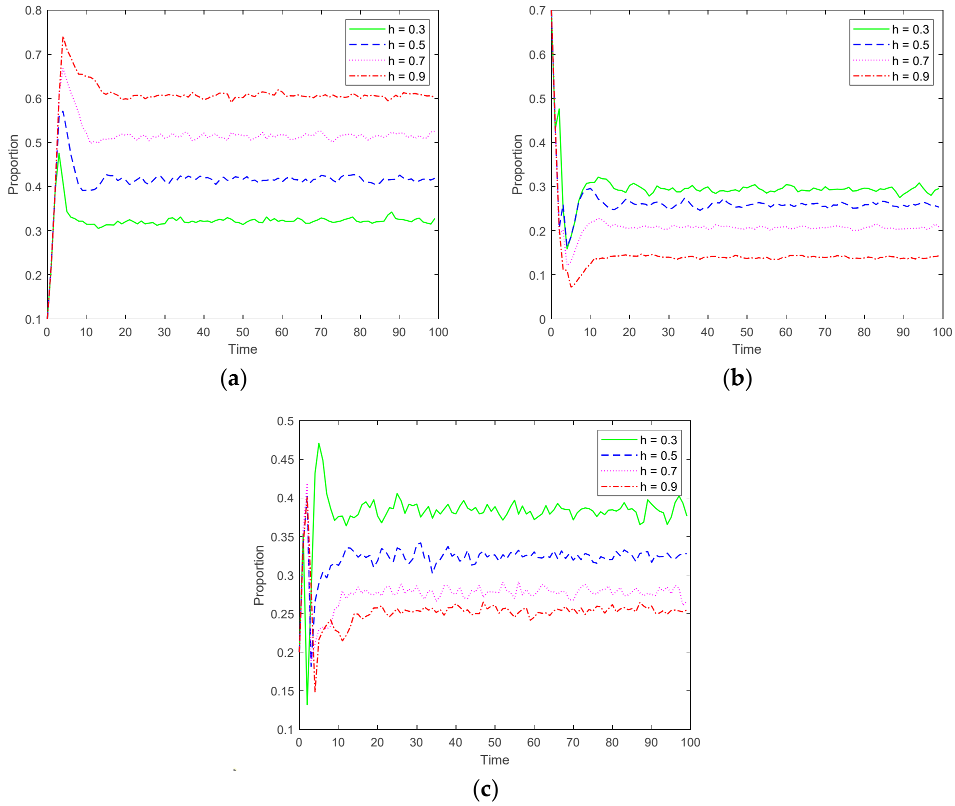

Figure 7. Impact of social climate level h: (**a**) high-quality green building enterprises; (**b**) traditional building enterprises; (**c**) low-quality green building enterprises.

When the level of social climate increases, the scale of HGB enterprises increases, and the scale of TB enterprises and LGB enterprises all decrease. Under the dissemination model of the CIC, the probability of conversion of potential consumers into traditional consumers decreases when the level of social climate increases; the probability of conversion of traditional consumers into high-quality green consumers increases, and the probability of converting into low-quality green consumers decreases, while the probability of high-quality green consumers converting into traditional consumers is decreasing. Overall, the strong social climate makes consumers interested in high-quality green buildings, the scale of the high-quality green consumer group increases, and the scale of traditional consumers and low-quality green consumers decreases. Thus, the revenue of HGB enterprises increases, and non-high-quality green building enterprises are converted to HGB enterprises under the driving force of interests, resulting in an increase in the number of HGB enterprises in the group. From Figure 7b,c, it can be seen that as the level of social climate increases, TB enterprises are more sensitive to it, while LGB enterprises are less sensitive to it, so improving the level of social climate will effectively promote the GTCEs.

4.2.2. Impact of the Carbon Price

The carton price p is set to 0, 50, 200, 500, and 1000, respectively, and the evolution of the group of construction enterprises is shown in Figure 8.

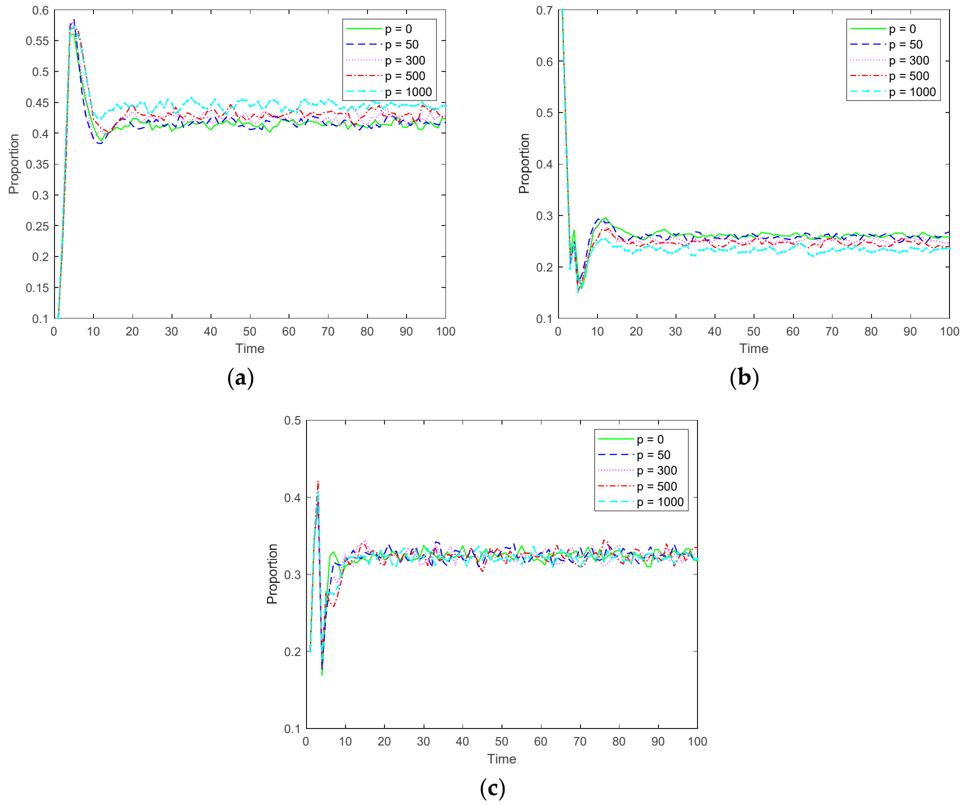

Figure 8. Impact of the carbon price p: (**a**) high-quality green building enterprises; (**b**) traditional building enterprises; (**c**) low-quality green building enterprises.

It can be seen that the scale of HGB enterprises increases with the increase in carbon price, and the scale of TB enterprises in the group decreases. Moreover, the role of low carbon prices is negligible, and a high carbon price has a certain promotion effect on the development of green buildings, and this result is similar to the research conclusion [32]. It should also be noted that the scale of LGB enterprises fluctuates around 0.32, which is due to the fact that the increase in the carbon price makes some LGB enterprises transform into HGB enterprises, but the transformation of TB enterprises into HGB enterprises is also transforming to LGB enterprises, which compensates for the decrease in LGB enterprises to a certain extent. Overall, when a carbon trading market exists, an appropriate increase in the carbon price will lead to a reduction in the scale of existing traditional building enterprises and an increase in the scale of green building enterprises, facilitating the GTCEs.

4.3. The Impact of Construction Enterprises' Own Factors on the GTCEs

4.3.1. Impact of Benefit and R&D Investment

The values of R&D investment C are 10, 40, 70, 100, and 130, and the corresponding benefits R_1 are 580, 650, 740, 850, and 980, and the evolution of the group of construction enterprises is shown in Figure 9.

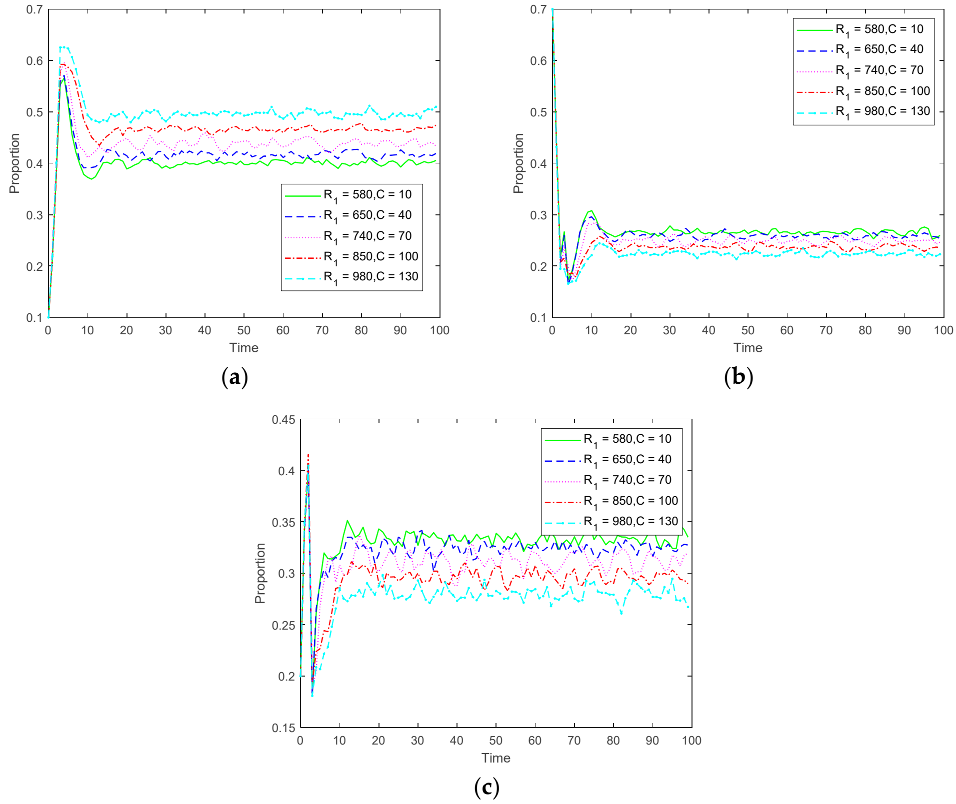

Figure 9. Impact of benefit R_1 and R&D investment C: (**a**) high-quality green building enterprises; (**b**) traditional building enterprises; (**c**) low-quality green building enterprises.

It can be seen that when the HGB enterprises increase their green R&D investment in order to obtain higher benefits, the scale of HGB enterprises increases, and the scale of LGB enterprises and TB enterprises gradually decreases. When the R&D investment is increased to obtain higher benefits, the non-high-quality green building enterprises will be driven by profit to choose the constructing high-quality green building strategy. Therefore, in the transformation process of construction enterprises, HGB enterprises can appropriately increase their R&D investment to improve the corresponding benefits, so as to attract other types of construction enterprises to learn and imitate.

4.3.2. Impact of Technology Level of the Construction Enterprises

When the technology level of the enterprise l takes the values of 0.3, 0.5, 0.7, and 0.9, respectively, the evolution of the group of construction enterprises is shown in Figure 10.

As can be seen from the figures, the scale of HGB enterprises has been increasing with the improvements in the technology level of the construction enterprises, and the scale of TB enterprises and LGB enterprises has been decreasing. From the consumer intention dissemination model, when the technology level of the construction enterprise is constantly improving, the consumer's recognition of the quality of the green building increases, and the interests of consumers in choosing HGBs are fundamentally guaranteed, which leads to an increase in the probability of low-quality green consumers and the traditional consumers convert into the high-quality green consumers, and therefore the scale of the high-quality green consumers is increasing, and then the scale of the HGB enterprises is increasing as well. The same can be obtained that with an improvement in the technology level of construction enterprises, the sensitivity of all three types of construction enterprises decreases, so the appropriate improvement in the technology level of green construction enterprises has a more positive impact on the GTCEs.

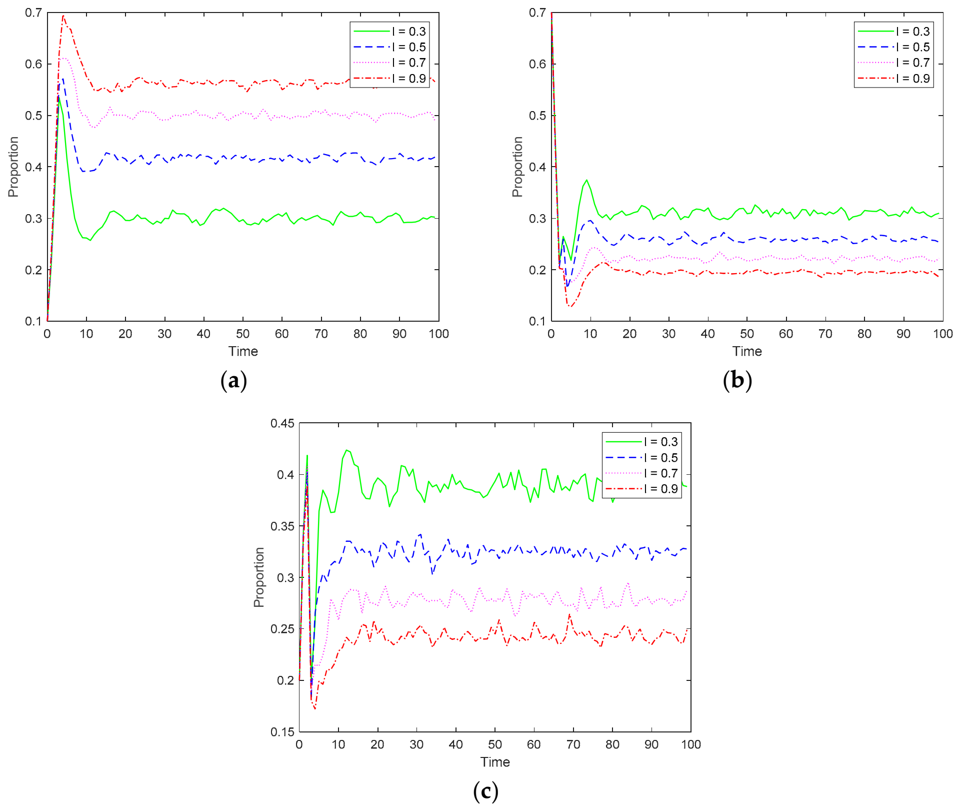

Figure 10. Impact of technology level of the construction enterprises l: (**a**) high-quality green building enterprises; (**b**) traditional building enterprises; (**c**) low-quality green building enterprises.

4.4. The Impact of Consumer Factors on the GTCEs

4.4.1. Impact of Consumers' Green Cognition Level

The evolution of the group of construction enterprises is shown in Figure 11 when consumers' green cognition level g = 0.3, 0.5, 0.7, 0.9.

It can be found that the scale of HGB enterprises increases with the level of green cognition of consumers increasing, and the scale of TB enterprises and LGB enterprises decreases accordingly. Therefore, when consumers' green cognition level increases, consumers' requirements and standards for green buildings increase, and they pursue higher-quality green buildings. At this time, in the consumer intention dissemination model, the probability of conversion of low-quality green consumers into high-quality green consumers, on the one hand, increases, and on the other hand, the probability of converting into traditional consumers decreases, and the number of high-quality green consumers in the consumer group continues to increase, and the corresponding scale of HGB enterprises increases. When g increases from 0.3 to 0.9, the scale of TB enterprises decreases from 0.31 to 0.20, while the scale of LGB enterprises decreases from 0.37 to 0.17, so increasing the level of green cognition of consumers has a more obvious inhibiting effect on LGB enterprises.

4.4.2. Impact of Consumers' Risk Perception Level

The consumers' risk perception level d is taken as 0.1, 0.3, 0.5, and 0.7, respectively, and the evolution of the group of construction enterprises is shown in Figure 12.

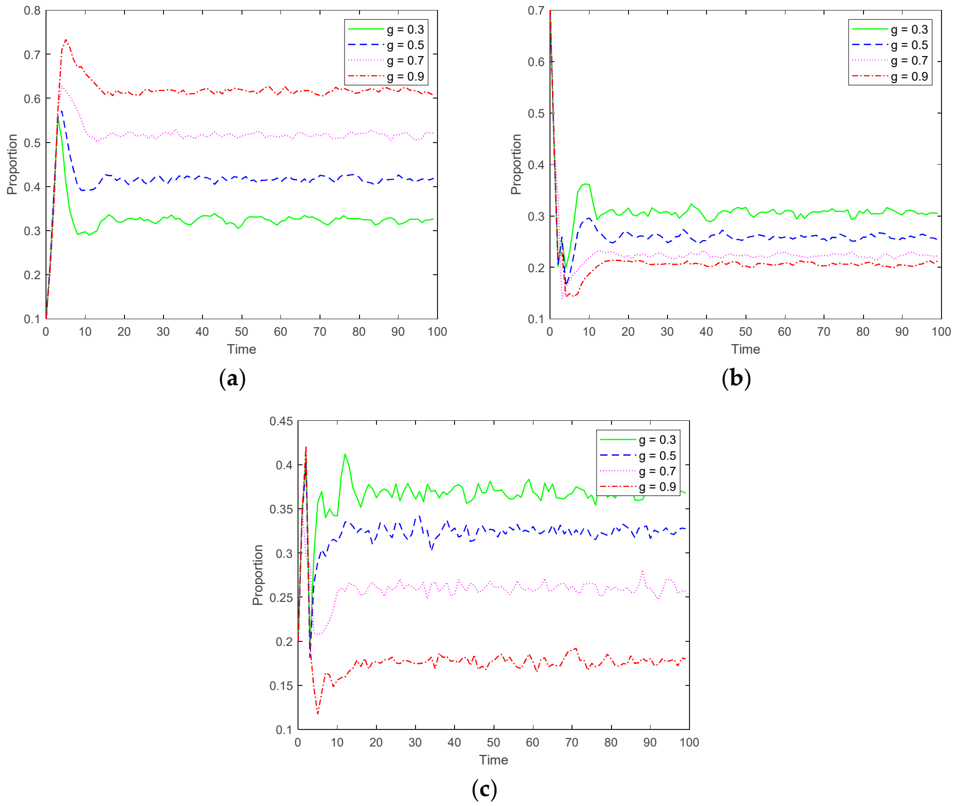

Figure 11. Impact of consumers' green cognition level *g*: (**a**) high-quality green building enterprises; (**b**) traditional building enterprises; (**c**) low-quality green building enterprises.

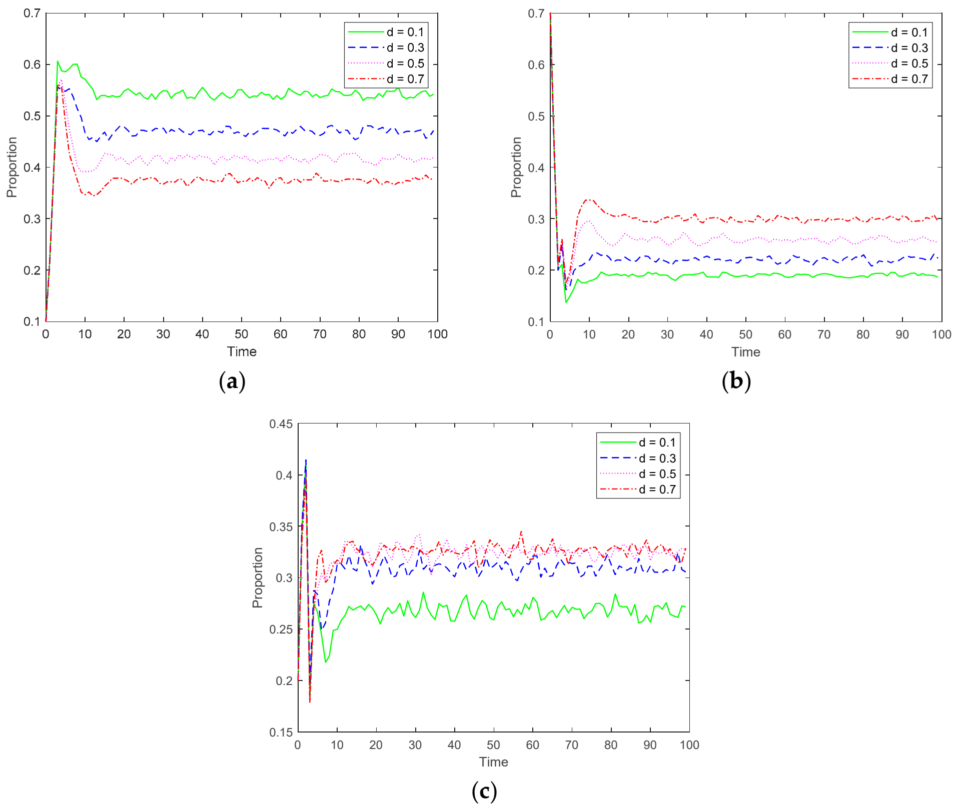

Figure 12. Impact of consumers' risk perception level *d*: (**a**) high-quality green building enterprises; (**b**) traditional building enterprises; (**c**) low-quality green building enterprises.

It can be seen that the scale of HGB enterprises continues to decrease and the scale of TB enterprises and LGB enterprises continues to increase as the consumers' risk perception level increases. According to the consumer intention dissemination model, when the consumer's risk perception level increases, consumers will be more inclined to choose conservative strategies to avoid losses. Thus, the probability of conversion of high-quality green consumers into low-quality green consumers increases, and the probability of low-quality green consumers converting into traditional consumers increases; at this time, the scale of high-quality green consumers is decreasing, and therefore, the scale of HGB enterprises is also decreasing. From Figure 12c, the higher level of consumer risk perception has no significant effect on the scale of LGB enterprises, i.e., LGB enterprises are less sensitive to the level of consumer risk perception.

5. Discussion

Based on the internal connection and structural characteristics of the construction enterprises group, this paper constructs a complex network-based game model for the evolution of the GTCEs group, describes the dynamic process of the conversion of the CIC by adopting the improved SIR dissemination model, and couples the two dynamic models with the revenue as a link, comprehensively imitating the dynamic change and interaction process of the two heterogeneous groups in the supply side and the demand side of the construction sector. Then, the evolution laws of the different impact factors on the GTCEs' groups are analyzed through numerical simulation.

Whether considering policies and measures on the supply side or factors affecting the CIC on the demand side, they all have an impact on the profitability of construction enterprises, which thus affects the eventual development of green buildings. For the supply side, increased green building benefits have a positive impact on the development of green buildings by construction enterprises [74], so increasing R&D investment directly improves the green economic benefits, which has a certain promotion for the GTCEs. However, large R&D cost inputs are also a major factor hindering construction enterprises from developing green buildings. As a common economic measure used by the government, government subsidies are effective in compensating for R&D cost inputs and thus facilitating enterprises to make green-decisions [75]. And the study shows that moderate subsidies have a significant impact on the GTCEs, while the sensitivity of construction enterprises to subsidies decreases with the increase in subsidies. When subsidies are used to attract a large number of enterprises to participate in the development of green buildings, the market share corresponding to each enterprise decreases significantly due to the fixed consumption side, and the increase in subsidies cannot compensate for the loss of market share, leading to the construction enterprises not choosing green strategies. Some scholars have also conducted statistics on the policies related to the development of green buildings in China, and the proportion of incentive policies has gradually decreased in its rapid development and maturity stages [16]. In addition, higher subsidies can also cause financial pressure on the government, so moderate subsidies are needed to achieve effective incentives. Penalties on non-high-quality green building enterprises are actually another form of subsidy, and mandatory regulatory measures can promote the development of green buildings. However, the penalties are based on damage to the interests of construction enterprises, so it can be conjectured that if there is an exit mechanism for enterprises when the gains from an increase in the share of the enterprise cannot meet the losses caused by the penalties, the enterprise may choose to opt-out in order to preserve its self-interests, and the size of the different types of enterprises will be stabilized within the acceptable gains

The introduction of a carbon trading market is another government measure, and studies have found that carbon trading has a positive impact on decision-making for green behaviors [76]. However, the study shows that a lower carbon price has a negligible effect on the GTCEs, and a higher carbon price has an effect on the GTCEs. The carbon trading proceeds account for a small proportion of the enterprise earnings and have little impact on the interests of enterprises. Tan et al. also pointed out that the carbon trading market is usually used as a non-profit and policy-oriented market in China, and its purpose is to promote the development of financial activities related to carbon trading so that the carbon prices in different regions and pilots are also affected by the regional market and policies [77]. Compared with the traditional trading market, the carbon trading market is not yet very active, and carbon trading in the construction sector is yet to be developed and improved.

In addition, previous studies have shown that green consumer behavior plays an important role in the green building market [78]. While the planned behavior theory suggests that behavioral intentions will affect individual behavior [10], the factors that affect individual behavioral intentions mainly include attitude, subjective standards, and perceived behavior. Yang et al. suggested that consumers' consumption habits, psychological perceptions, and trust in building quality also influence the CIC [39]. Consumers' green awareness is the market driver for enterprises to carry out green behaviors [79], so it is necessary to explore the relevant factors affecting consumers' green consumption intentions for the GTCEs. Considering the heterogeneity of consumer groups, this study analyzes the impact of the relevant factors affecting green consumption on the GTCEs from the level of social atmosphere, the government's publicity and education, the technological level of enterprises, the level of green cognition, and the level of consumer risk perception. Compared with the supply side, the pulling effect of the consumer side on GTCEs is obvious, and will not hurt the interests of enterprises. When formulating policies, the government should also consider policies aimed at arousing consumers' green recognition. Therefore, measures should be taken for both the supply side and the demand side to promote the comprehensive and high-quality development of green buildings.

6. Conclusions and Policy Implications

6.1. Conclusions

The GTCEs are an important way to develop green buildings and realize the goal of "double carbon". In this study, considering the heterogeneity and interaction between the supply-side and demand-side groups, an evolutionary game model based on complex networks is constructed on the demand side, and an improved SIR dissemination model is constructed on the supply side, and the above models are coupled to explore the laws of GTCEs. The following conclusions can be drawn:

(1) Increased R&D investment by enterprises for higher market returns, government subsidies, penalties, and carbon prices have a positive impact on the development of GTCEs. When green building enterprises increase R&D investment to obtain higher returns, the higher economic benefits will attract other non-high-quality building enterprises to transform, but the higher returns correspond to more R&D investment in the early stage, which often becomes an obstacle to hinder the GTCEs. Government subsidies can compensate for the cost of enterprises to a certain extent, but the results show that with an increase in subsidies, the sensitivity of enterprises to them decreases; that is, the incentive effect of higher subsidies is not ideal, and the higher subsidies will increase the burden on government's finances. In addition, when government penalties are raised, the size of non-high-quality green building enterprises decreases, and sensitivity to penalties increases, which may be due to the prospect theory, i.e., enterprises will be more sensitive to losses than gains. However, penalties are premised on the loss of enterprise benefits, so higher government subsidies and penalties are not permanent measures. In addition, in the carbon trading market, a lower carbon price has a negligible driving effect, and a higher carbon price has a certain driving effect, which is caused by the fact that carbon trading revenues account for a relatively small portion of enterprise earnings and that different types of enterprises perform differently in the carbon trading market. Therefore, in order to the GTCEs, enterprises can appropriately increase investments in R&D to increase the direct green economic benefits, and at the same time, in order to ensure the incentive effect of government policy, considering the different types of construction enterprises, the government should set reasonable subsidies, penalties, and carbon prices.

(2) The level of social climate, the level of government publicity and education, the technology level of construction enterprises, the level of green cognition of consumers, and the level of risk perception will directly affect the number of consumers with different consumption intentions in the consumer group, thus affecting the GTCEs. Green consumer demand affects green building development, and consumer intention affects consumer behavior; as a heterogeneous group, there are many factors that affect the CIC. When the factors affecting the CIC change, the state of consumers with different intentions to consume will change, corresponding to changes in the number of consumers, resulting in changes in the demand for different types of construction products, which, in turn, affects the economic returns of construction enterprises. Driven by interests, the decision-making of construction enterprises will change, and the corresponding scale of construction enterprises will also change. Therefore, in order to better promote the GTCEs, increasing attention to the factors that affect intentions to consume on the consumer side will enhance the green consumption of consumers on the demand side and provide a strong driving force for the GTCEs on the supply side.

(3) The participation of the government, supply side, and consumer side are the key factors affecting the GTCEs. The enterprise's own factors and choices, made by the construction enterprise itself, directly affect the results of the green transformation of the construction enterprise group, and the government's incentives and regulatory measures also affect the effectiveness of the GTCEs. In addition, compared with other measures, stable green consumer market demand is the driving force for the long-term development of green building. The government, construction enterprises, and consumers are mutual influence, in order to the GTCEs should take into full consideration the relationship between all parties and interactions so as to achieve multi-party synergies and stable and sustainable development.

6.2. Policy Implications

In response to the above findings and analytical discussions, the following policy implications can be made:

(1) The government should take into account the specific development and market situation when formulating appropriate incentives or regulatory measures for the supply side. Research has shown that moderate subsidies and penalties have a positive impact on the green transformation of construction enterprises, excessive subsidies have no significant change in incentive effects, and excessive penalties damage the interests of enterprises, so moderate incentives and regulatory measures are necessary. In addition, a lower carbon price has little impact on the development of green buildings, and when a carbon trading market exists, it is also necessary to set an appropriate carbon price to realize the regulatory role of the carbon trading market. For different types of construction enterprises existing in the market, green building certification should be conducted and incentives or regulatory measures can be targeted.

(2) Increase attention to consumers on the demand side and implement richer service policies. Green consumption has a great impact on the GTCEs, and studies have shown that the social atmosphere, government publicity and education, consumers' green awareness, construction enterprises' technology, and consumers' risk perception all affect the CIC. Compared with measures on the supply side, stimulating the potential of green consumption is key to the long-lasting development of green buildings. Therefore, service policies and measures targeted at consumers can be formulated to strengthen the publicity and education of consumers. Online resources such as print media, advertising, social media, and self-media can be used to carry out diversified and multi-channel publicity and education, popularize green building knowledge, and create a strong green atmosphere. In addition, it is also possible to go into the community, the streets, and other places and hire professionals or practitioners in construction enterprises to carry out offline knowledge popularization and explanations of problems. At the same time, build and improve the information disclosure mechanism, synchronize the information of construction enterprises,

increase the channels for consumers to obtain professional information, regulate the quality of buildings developed by enterprises, enhance the confidence of consumers, strengthen the channels of communication between the government, enterprises, and consumers, understand the public demand, and enhance the perception of consumers.

(3) Supply-side and consumer-side measures should complement each other and develop together. The development of green buildings cannot be separated from the joint efforts of the government, construction enterprises, and consumers, and different measures can be implemented for different stages of green building development and different subjects. In the early stage of green building development, consumer awareness of green consumption is low, and we should appropriately rely on the enterprise itself and government incentives to guide the development of the first. With the development of green buildings and green consumer awareness, in addition to supply-side measures, it is more important to strengthen the control and guidance of consumers on the demand side.

Starting from the internal and external factors affecting the evolution of the strategies of construction enterprises, this paper considers the impact of different factors on the GTCEs in a more comprehensive way. The limitations of the study are that the impact of some factors, such as the diffusion rules of green technology in the evolutionary game of green transformation of a group of construction enterprises have not been fully considered. Furthermore, the factors affecting the green transformation of the construction enterprise group are mostly stochastic, which will lead to a certain degree of randomness in the evolution of the green transformation of the construction enterprise group. Meanwhile, how to simulate and analyze the stochastic evolution law of the group is also an issue that needs further research.

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