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Decoding Strategies in Green Building Supply Chain Implementation: A System Dynamics-Augmented Tripartite Evolutionary Game Analysis Considering Consumer Green Preferences

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Abstract: The building sector accounts for one-third of global greenhouse gas emissions, representing a significant environmental challenge in the 21st century. Green supply chain management is considered an effective approach to achieving green transformation in the construction industry. However, the green building supply chain (GBSC) involves multiple stakeholders, necessitating integrated consideration of various participants to ensure efficient GBSC implementation. In this context, and accounting for consumer green preferences, this paper identifies the government, enterprises, and consumers as key stakeholders. A tripartite evolutionary game model is established, and the influence of the participants' strategic choices on the system equilibrium is analyzed. The model's validity was assessed through sensitivity analysis and by comparing its outputs with findings from the existing literature. The findings show that: (1) Significant interdependence exists among GBSC participants. (2) The system will eventually tend toward an equilibrium characterized by active enterprise implementation and consumer green consumption, reducing the need for government intervention. (3) The sensitivity analysis shows that green consumption is significantly affected by the extra cost and perceived environmental benefits. These conclusions suggest that governments should build a collaborative governance system, implement dynamic and precise supervision of enterprises in stages, and optimize the incentive design for consumers to promote the implementation of the green building supply chain.

Keywords: green building; green building supply chain; tripartite evolutionary game; system dynamics; decision-making behavior; green preferences

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1. Introduction

The construction sector's escalating carbon emissions present a critical environmental challenge [1]. Building material-related emissions are projected to increase by 3.5 to 4.6 Gt CO_2eq per year between 2020 and 2060 [2]. These emissions are deeply embedded in the construction supply chain, spanning raw material extraction, manufacturing, transportation, and building operations. Isolated efforts in single sectors (e.g., energy-efficient technologies or green certification) have proven insufficient to curb systemic emissions, necessitating a holistic approach to green building supply chain (GBSC) management.

Governments globally have implemented various policies aimed at promoting green emission reductions. These include fostering carbon trading schemes and enforcing stricter environmental regulations to mitigate the negative environmental impacts of construction activities. At the 2023 United Nations Climate Change Conference (COP28), parties to the Paris Agreement reached a landmark consensus on a legally binding global climate agreement, aiming to cap the global temperature increase at <2 °C above pre-industrial levels [3]. The European Union Emissions Trading System (EU-ETS), one of the world's most influential carbon markets, has become a key market mechanism for driving emission reductions within the region [4]. The Chinese government, in its Made in China 2025 and Industrial Green Development Plan (2021–2025), explicitly outlined the acceleration of a domestic green certification system centered on green factories, green products, and green supply chains [5]. However, the effectiveness of such policies hinges on multi-stakeholder coordination across the supply chain. For instance, carbon trading mechanisms require synchronized data transparency among suppliers, contractors, and regulators to prevent leakage effects [6]. Systematic analysis of GBSC dynamics is therefore imperative to align decarbonization targets with practical supply chain operations.

The terms green building, sustainable building, and high-performance building are often used synonymously in the existing literature, with zero-energy buildings frequently considered a subcategory of green building [7]. Studies have shown that the life cycle CO_2 emissions of green buildings are significantly lower compared to conventional structures, exhibiting reductions of approximately 10% for residential and 32% for commercial buildings, respectively [8]. In recent years, with the gradual deepening of the concept of sustainable development, research on green buildings has exhibited a diversified trend. Research on green buildings encompasses the entire building life cycle, investigating energy efficiency and environmental protection at various stages, including design, construction, and operation [9]. The integration of technologies like the Internet of Things (IoT), cloud computing, and big data has significantly improved the energy, water, and material efficiency of green buildings, while also reducing greenhouse gas emissions [10–13]. Research indicates that green buildings, through enhanced energy efficiency, the use of sustainable materials, and optimized design, can significantly reduce energy consumption and carbon emissions, thereby substantially mitigating their negative environmental impact over their life cycle [14–18].

The increasing global emphasis on environmental protection and resource conservation has led to the widespread adoption and development of green supply chain management (GSCM) in the construction industry [19]. Green Building Supply Chain (GBSC) encompasses the life cycle, ranging from the extraction, processing, and transportation of raw materials to construction, operation, and ultimately, demolition and recycling of buildings [20,21]. This process not only involves the environmental impact assessment of construction projects but also includes a comprehensive consideration of the environmental, social, and economic impacts of each link in the supply chain [22–24]. The implementation of GBSC can effectively mitigate the negative environmental impacts of construction projects throughout their life cycle, while enhancing resource efficiency and promoting ecological balance, ultimately contributing to sustainable development in the construction industry [25]. However, due to the complexity of the construction supply chain and the involvement of multiple stakeholders, the implementation of GBSC faces numerous challenges, such as information asymmetry, inadequate cooperation mechanisms, and uneven distribution of benefits [26,27].

The GBSC is a complex system with green building products as the final output. Through the collaborative efforts of multiple stakeholders, it aims to maximize economic benefits while emphasizing the minimization of environmental impact [28]. Collaborative actions among all links and stakeholders within the construction supply chain are indispensable to the carbon reduction process [29]. Achieving carbon emission reduction targets in the construction industry is challenging and cannot be accomplished by relying on a single link or entity alone [30]. During the green transformation of supply chains, the high upfront investment costs coupled with the less obvious short-term benefits lead to some enterprises holding a negative attitude towards the promotion of green building supply chains [31,32]. While government incentives have demonstrated partial effectiveness in stimulating corporate engagement, they have also inadvertently enabled superficial compliance through greenwashing practices [33,34]. Consumers, as the demand side of the final products in the green building supply chain, play a crucial role in promoting the green building supply chain through their consumption behavior [35]. As sustainability concepts become more firmly entrenched and economic prosperity ascends, consumers are increasingly aware of the importance of green and low-carbon practices [36]. Through controlled experiments, Tezer and Bodur (2023) revealed that green products significantly increase consumers' experiential enjoyment relative to traditional alternatives, defining this as the "green consumption effect" [37]. Rustam et al. demonstrate that a firm's sustainability disclosure and environmental responsiveness serve as pivotal drivers of green consumption practices [38]. Chen et al. discussed the impact of the green premium of different products on consumers' green preferences [39]. The factors that affect consumer green consumption may be different in different industries, and it is crucial to consider the factors that affect consumer preferences for engaging in green building consumption.

Existing relevant research primarily centers on green buildings and the dimensions of their supply chains [40]. There is a lack of research providing a systematic analysis of the entire supply chain. Although some studies introduce evolutionary game theory to analyze the implementation path of green building supply chains, they still have the following limitations: (1) The analytical framework restricts participants to dyadic government-enterprise interactions, neglecting the moderating effect of consumer green preferences [41]; (2) Most existing studies only focus on government incentive mechanisms, while ignoring the synergistic mechanism of rewards and punishments and the resulting dynamic regulation [42]. Given the preponderant role of the government in implementation, and considering the bounded rationality and reciprocal learning characteristics of the government, enterprises, and consumers, evolutionary game theory affords an appropriate means for deciphering the underlying mechanisms. System dynamics excel at analyzing the feedback loops within complex systems and simulating long-term dynamic changes. Integrating this methodology with evolutionary game theory provides a complementary approach, enabling both the analysis of strategic interactions and the investigation of the overall system's dynamic feedback mechanisms.

This study innovatively integrates tripartite evolutionary game theory with system dynamics while considering consumer green preferences and systematically investigating the strategic decision-making processes of governments, enterprises, and consumers in promoting green building supply chains. Compared with existing literature, the distinctive features of this model manifest in three aspects: (1) Incorporating consumers as active participants by introducing decision-making variables for this stakeholder group; (2) considering the government's synergistic reward and punishment mechanism and constructing a mixed policy toolset including government penalties and subsidies; (3) Advancing methodological integration by combining static analytical frameworks with dynamic simulation modeling, constructing a system dynamics model based on the tripartite evolutionary game framework. The theoretical contribution of this research addresses critical gaps in current scholarship by providing novel perspectives and methodological approaches for green building supply chain studies. In addition, the findings provide strategic recommendations for the government, including building a collaborative governance system, implementing phased dynamic and precise regulation of enterprises, and optimizing consumer incentive design.

This study aims to comprehensively analyze the strategic interactions among key stakeholders and the factors influencing their decisions within the GBSC through the application of a tripartite evolutionary game and system dynamics approach. The ultimate objective is to foster active engagement and support from all parties for the holistic implementation of the GBSC. To achieve these objectives, this research first delineates the fundamental principles and methodologies of tripartite evolutionary game theory and system dynamics. Subsequently, research hypotheses are formulated, and a tripartite evolutionary game model involving government, enterprises, and consumers is constructed, followed by a stability analysis of equilibrium points. Building upon the evolutionary game model, a system dynamics model is then developed to simulate GBSC implementation, enabling an in-depth analysis of the influence mechanisms underlying each stakeholder's strategy. Simulation analyses are conducted for both pure and mixed strategies, alongside a sensitivity analysis to assess the robustness of the results. Finally, based on a synthesis of these findings, the study provides a nuanced discussion, proposes specific policy recommendations, and acknowledges potential limitations of the research.

2. Methods

Within the framework of classical game theory, research entities are often assumed to be perfectly rational, which neglects the capacity for analysis, reasoning, and learning inherent in human behavior within economic contexts [43]. This study employs tripartite evolutionary game theory, which posits that participants are boundedly rational economic agents [44]. These agents typically adopt strategies based on a learning process rather than rational choice. Every strategy choice of participants has its corresponding strategic revenue and the probability of participants choosing the strategy. The game model of the green building supply chain contains three participants, namely the government, enterprises, and consumers. In this tripartite evolutionary game, the government can choose intervention or non-intervention, enterprises can choose to implement GBSC or not, and consumers can choose green consumption or not. In this study, the term 'intervene' is used to describe the government's actions within the GBSC. This intervention encompasses both: (1) direct oversight and regulation of producers through the establishment and enforcement of environmental standards, and the provision of rewards or penalties for compliance or non-compliance, respectively; (2) indirect influence on consumer behavior through incentives such as subsidies and tax allowances, and the dissemination of information promoting green building practices. The game relationship among the three is shown in Figure 1.

System Dynamics (SD), a methodological method for the dynamic analysis of complex systems, was developed by Professor Forrester at the Massachusetts Institute of Technology in the late 1950s [45]. This approach is fundamentally concerned with elucidating causal relationships and the resultant dynamic behavior within systems, explicitly recognizing that multiple factors interact simultaneously. Unlike static analysis, SD emphasizes the endogenous drivers of system behavior, focusing on how internal dynamics, rather than exogenous forces, contribute to patterns of growth, decline, and fluctuation. The methodology enables a holistic perspective on system behavior by incorporating feedback mechanisms and time delays. Increasingly, SD is being adopted across diverse research domains, including the study of evolutionary processes, simulation modeling, and risk assessment in complex systems [46–48]. Its capacity to model the long-term and unintended consequences of interventions, while providing insights into the dynamic effects of various policies and operational practices has made it a powerful tool in addressing a wide range of systemic challenges [49,50].

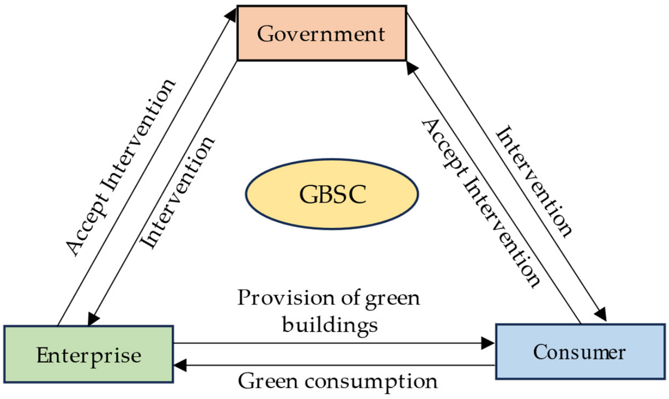


Figure 1. The tripartite game-theoretic relationship within the green building supply chain (GBSC).

In summary, building upon the tripartite evolutionary game theory, this paper employs a system dynamics model to explore the strategies of the three participants involved in the implementation of a green building supply chain. Figure 2 presents the framework of this study.

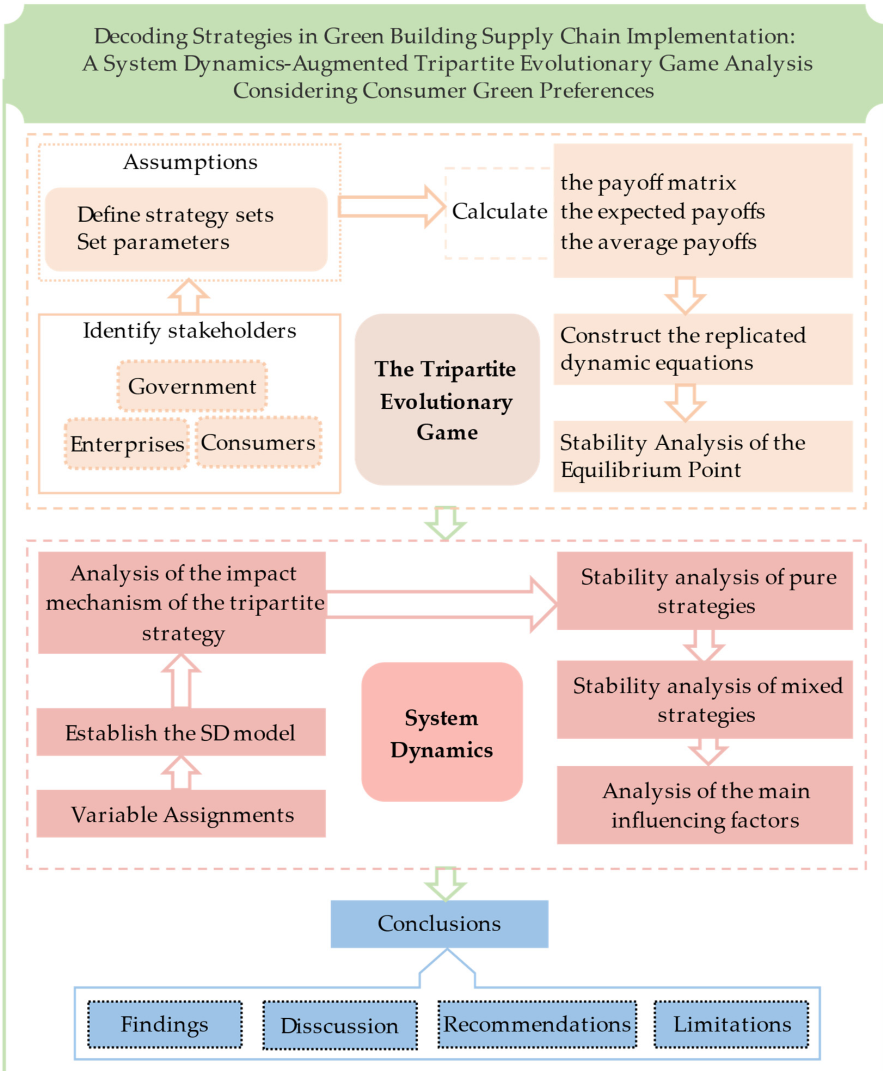


Figure 2. Research framework.

3. Tripartite Evolutionary Game Model and Analysis

3.1. Basic Hypothesis

We make the following assumptions about the model with reference to relevant research in the field of tripartite evolutionary games [51–53]:

Assumption 1. *The government, enterprises, and consumers can only make limited rational decisions in the case of incomplete information. All of them need to make adjustments by analyzing the decision-making environment and the strategies of other participants. After a period of time, the system can reach a certain stable state* [54].

Assumption 2. *The government has two strategies available during the implementation of the GBSC. The first strategy is to intervene in the behavior of the remaining participants in the GBSC implementation process, which is referred to as intervention. And the second strategy is not to intervene, which is referred to as non-intervention. Choosing the intervention strategy requires the government to invest in costs. The government chooses between the two strategies for intervention with probability* x*. The probability that the government chooses non-intervention is* $1 - x$, $x \in [0, 1]$.

Assumption 3. *The enterprise has two strategies available during the implementation of the GBSC. The first strategy is to implement the GBSC, which is referred to as implementation. The second strategy is not to implement the GBSC, which is referred to as non-implementation. When the enterprise chooses the implementation strategy, it must consider green factors throughout the life cycle. This involves investing in additional technology, resources, and other costs. In return, the enterprise may be eligible for government subsidies to support these sustainable efforts. The enterprise chooses the non-implementation strategy, which can save costs but result in fines. The enterprise chooses between the two strategies for implementation with probability* y*. The probability that the enterprise chooses the non-implementation is* $1 - y$, $y \in [0, 1]$.

Assumption 4. *As the end-user in the GBSC, the consumer has two strategies available during the implementation of the GBSC. The first strategy is to purchase green buildings, which is referred to as green consumption. The second strategy is to buy non-green buildings, which is referred to as non-green consumption. The consumer who chooses the green consumption strategy can obtain government subsidies and environmental benefits but has to pay some extra costs. The consumer chooses between the two strategies for green consumption with probability* z*. The probability that the consumer chooses the non-green consumption strategy is* $1 - z$, $z \in [0, 1]$.

With reference to the relevant literature, the parameters set in this paper pertaining to the strategies of the government, enterprises, and consumers are formulated as as presented in Table 1 [54,55]:

Table 1. Parameter definition.

Stakeholders	Symbols	Descriptions
Government	W	The cost incurred in supervising the enterprise's actions
	P	Government Penalties on Enterprises
	S_1	Government subsidies for enterprises to implement the green building supply chain (GBSC)
	S_2	Government subsidies for consumers to purchase green buildings
	G	Government's social benefits derived from the implementation of the GBSC, encompassing economic growth, environmental improvement, and enhanced urban competitiveness
	L	The loss in government reputation primarily resulting from a failure to effectively intervene in the implementation of GBSCs by enterprises.

Table 1. *Cont.*

Stakeholders	Symbols	Descriptions
Enterprise	C_1	The cost of not implementing the GBSC
	R_1	Revenue from not implementing the GBSC
	C_2	Extra costs for implementing the GBSC
	R_2	Additional revenue from implementing the GBSC when the government intervenes and consumers choose green consumption
	R_3	Additional revenue from implementing the GBSC when the government intervenes and consumers choose green consumption
Consumer	C_3	The cost of non-green consumption
	R_4	Revenue from non-green consumption
	C_4	The extra cost of green consumption
	R_5	Additional revenue from green consumption
	C_5	Additional cost of green consumption when enterprises do not implement the GBSC

Government-related parameters: W represents the cost incurred by the government when supervising the behavior of enterprises. P represents the penalty imposed by the government on enterprises that fraudulently implement the GBSC. S_1 represents government subsidies for enterprises to implement the GBSC; S_2 represents the government subsidies for consumers purchasing green buildings; G represents the social benefits derived from the implementation of the GBSC, encompassing economic growth, environmental improvement, and enhanced urban competitiveness. L represents the loss in government reputation primarily resulting from a failure to effectively intervene in the implementation of the GBSC by enterprises.

Enterprise-related parameters: C_1 represents the cost when enterprises do not implement the GBSC. R_1 represents the revenue when the enterprise does not implement the GBSC. C_2 represents the extra costs for enterprises to implement the GBSC, such as resources to establish and maintain the green supply chain, and investment in green technology research and development. R_2 represents the additional revenue obtained by enterprises when the government intervenes and consumers choose green consumption. R_3 represents the additional revenue obtained by the enterprise when the government does not intervene and consumers choose green consumption, including the increase in revenue caused by green consumption and the improvement of the enterprise's reputation caused by active green emission reduction, so the value is $0 < R_2 < R_3$.

Consumer-related parameters: C_3 represents the cost incurred by consumers when choosing non-green consumption. R_4 represents the revenue obtained by consumers when choosing non-green consumption. C_4 represents the extra cost incurred by consumers when choosing green consumption, primarily reflecting the price gap between green and non-green buildings. R_5 represents the additional revenue obtained by consumers when choosing green consumption, mainly attributed to the perceived green effectiveness. C_5 represents the consumer's additional cost of green consumption when enterprises do not implement the GBSC, for instance, the extra costs associated with proactively selecting green building materials and independently installing new ventilation systems.

3.2. Establishment of Tripartite Evolutionary Game Model

Based on the aforementioned assumptions and parameters, this study takes the government as an example to calculate the payoff matrices. When the GBSC is successfully implemented, the social benefits that the government can generate from it are denoted as G. In this case, if the government adopts an intervention strategy, the cost that needs to be borne by the government is W, and the subsidies that need to be paid are S_1 and S_2, so the government's benefit is G-W-S_1-S_2. The same can be conducted to calculate the benefits of the remaining participants.

The resulting payoff matrices for the government, enterprises, and consumers, based on the aforementioned assumptions and parameters, are presented in Table 2.

Table 2. Payoff matrices for the government, enterprises, and consumers.

Game Participants				Consumer	
				Green Consumption	**General Consumption**
Government	Intervention	Enterprise	Implementation	$G-W-S_1-S_2$ $R_1+R_2-C_1-C_2+S_1$ $R_4+R_5-C_3-C_4+S_2$	$G-W-S_1$ $R_1+S_1-C_1-C_2$ R_4-C_3
			Non-implementation	$P-W$ R_1+C_1-P $R_4+R_5-C_3-C_5$	$P-W$ R_1+C_1-P R_4-C_3
	Non-intervention	Enterprise	Implementation	G $R_1+R_3-C_1-C_2$ $R_4+R_5-C_3-C_4$	G $R_1-C_1-C_2$ R_4-C_3
			Non-implementation	$-L$ R_1-C_1 $R_4+R_5-C_3-C_5$	$-L$ R_1-C_1 R_4-C_3

Through the tripartite evolutionary game payoff matrix, we can further derive the expected and average payoffs of the government, enterprises, and consumers. Assuming the expected payoff for the government choosing the intervention strategy is U_{11}, the expected payoff for the non-intervention strategy is U_{12}, and the average expected payoff is U_1, then

$$U_{11} = yz(G-W-S_1-S_2) + y(1-z)(G-W-S_1) + (1-y)z(P-W) + (1-y)(1-z)(P-W) \tag{1}$$

$$U_{12} = yzG + y(1-z)G + (1-y)z(-L) + (1-y)(1-z)(-L) \tag{2}$$

$$U_1 = xU_{11} + (1-x)U_{12} = yG - L + Lx + Ly + Px - Wx - Lxy - Pxy - xyS_1 - xyzS_2 \tag{3}$$

The replication factor dynamic equation describes the evolution of the probability of participants [56]. The replicator dynamic equation for the government's decision-making, derived from the replicator dynamics equation of evolutionary game theory, is

$$F(x) = dx/dt = x(U_{11} - U_1) = x(x-1)(W - P - L + yL + yP + yS_1 + yzS_2) \tag{4}$$

Similarly, assuming the expected payoffs for enterprises choosing the implementation strategy and the non-implementation strategy are U_{21} and U_{22}, respectively, and the average expected payoff is U_2, then

$$U_{21} = xz(R_1+R_2+S_1-C_1-C_2) + x(1-z)(R_1+S_1-C_1-C_2) + (1-x)z(R_1+R_3-C_1-C_2) + (1-x)(1-z)(R_1-C_1-C_2) \tag{5}$$

$$U_{22} = xz(R_1+C_1-P) + x(1-z)(R_1+C_1-P) + (1-x)z(R_1-C_1) + (1-x)(1-z)(R_1-C_1) \tag{6}$$

$$U_2 = yU_{21} + (1-y)U_{22} = R_1 - C_1 + 2xC_1 - yC_2 - xP - 2xyC_1xy + xyP + xyS_1 + yzR_3 + xyzR_2 - xyzR_3 \tag{7}$$

Similarly, the replicator dynamic equation for enterprises' decision-making is

$$F(y) = dy/dt = y(U_{21} - U_2) = -y(y-1)(xP - 2xC_1 - C_2 + xS_1 + zR_3 + xzR_2 - xzR_3) \tag{8}$$

Similarly, assuming the expected payoffs for the consumer choosing the green consumption strategy and the non-green consumption strategy are U_{31} and U_{32}, respectively, and the average expected payoff is U_3, then

$$U_{31} = xy(R_4 + R_5 - C_3 - C_4 + S_2) + x(1-y)(R_4 + R_5 - C_3 - C_5) + (1-x)y(R_4 + R_5 - C_3 - C_4) + (1-x)(1-y)(R_4 + R_5 - C_3 - C_5) \tag{9}$$

$$U_{32} = xy(R_4 - C_3) + x(1-y)(R_4 - C_3) + (1-x)y(R_4 - C_3) + (1-x)(1-y)(R_4 - C_3) \tag{10}$$

$$U_3 = zU_{31} + (1-z)U_{32} = R_4 - C_3 - zC_5 + zR_5 - yzC_4 + yzC_5 + xyzS_2 \tag{11}$$

Similarly, the replicator dynamic equation for consumer strategy is

$$F(z) = dz/dt = z(U_{31} - U_3) = -z(z-1)(R_5 - C_5 - yC_4 + yC_5 + xyS_2) \tag{12}$$

Combining the replicator dynamic equations $F(x)$, $F(y)$, and $F(z)$ forms a three-dimensional dynamic system describing the evolutionary dynamics of the government, enterprises, and consumers.

3.3. Stability Analysis of the Equilibrium Point

A strategy that results in a dynamic equilibrium as participants adjust their strategies to maximize their interests is termed an evolutionarily stable strategy (ESS) [57]. Before determining the evolutionarily stable strategies, the equilibrium points of the evolutionary game must be identified. Setting $F(x) = 0$, $F(y) = 0$, and $F(z) = 0$, where the change rate of the system's strategy choices is zero, yields 15 equilibrium solutions for the dynamic system. Among these, there are eight pure strategy equilibrium solutions: $A_1(0,0,0)$, $A_2(0,0,1)$, $A_3(0,1,0)$, $A_4(1,0,0)$, $A_5(0,1,1)$, $A_6(1,0,1)$, $A_7(1,1,0)$, $A_8(1,1,1)$. The asymptotic stability of A_1 to A_8 can be determined using the local stability analysis method of the Jacobian matrix.

The corresponding Jacobian matrix J for the tripartite evolutionary game model is

$$J = \begin{bmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} & \frac{\partial F(x)}{\partial z} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} & \frac{\partial F(y)}{\partial z} \\ \frac{\partial F(z)}{\partial x} & \frac{\partial F(z)}{\partial y} & \frac{\partial F(z)}{\partial z} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \tag{13}$$

where:

$$a_{11} = (2x-1)(W - P - L + yL + yP + yS_1 + yzS_2) \tag{14}$$

$$a_{12} = x(x-1)(L + P + S_1 + zS_2) \tag{15}$$

$$a_{13} = xy(x-1)S_2 \tag{16}$$

$$a_{21} = -y(y-1)(P - 2C_1 + S_1 + zR_2 - zR_3) \tag{17}$$

$$a_{22} = (1-2y)(xP - 2xC_1 - C_2 + xS_1 + zR_3 + xzR_2 - xzR_3) \tag{18}$$

$$a_{23} = -y(y-1)(R_3 + xR_2 - xR_3) \tag{19}$$

$$a_{31} = -yz(z-1)S_2 \tag{20}$$

$$a_{32} = -z(z-1)(C_5 - C_4 + xS_2) \tag{21}$$

$$a_{33} = (1-2z)(R_5 - N_3 - yC_4 + yC_5 + xyS_2) \tag{22}$$

Taking the pure strategy equilibrium solution $A_1(0,0,0)$ as an example, we discuss the conditions required for the system to satisfy asymptotic stability. Substituting the equilibrium point $A_1(0,0,0)$ into the Jacobian matrix J, we obtain the Jacobian matrix of the system at this point as:

$$J_1 = \begin{bmatrix} L+P-W & 0 & 0 \\ 0 & -C_2 & 0 \\ 0 & 0 & R_5-C_5 \end{bmatrix} \tag{23}$$

Consequently, as shown in Table 3, the characteristic values of the Jacobian matrix are $\lambda_2 = L+P-W$, $\lambda_2 = -C_2$, and $\lambda_3 = R_5 - C_5$. Similarly, substituting the remaining equilibrium points into the Jacobian matrix yields the characteristic values corresponding to each equilibrium point. According to the first Lyapunov method, if all characteristic values of the Jacobian matrix corresponding to an equilibrium point are less than 0, then that equilibrium point is asymptotically stable and represents an evolutionarily stable strategy [58]. The equilibrium point is unstable if all characteristic values are greater than 0. If one or two characteristic values exceed 0, the equilibrium point is a saddle point. Table 1 shows the characteristic values and their signs at equilibrium points A_1 to A_8. "+" indicates characteristic values greater than 0, "−" indicates characteristic values less than 0, and "*s*" indicates undetermined signs. While the stability of the equilibrium points can be determined by the local stability of the Jacobian matrix, the positive or negative signs of some characteristic values remain uncertain due to the indeterminate values of the variables in this study, thus hindering the determination of the existence of stable equilibrium points. Therefore, this paper utilizes Vensim PLE 10.2.2 to establish a system dynamics model to analyze the implementation effects under specific initial values and the influence of different initial values on the tripartite evolutionary game process.

Table 3. Equilibrium point characteristic value and stability judgment.

Equilibrium Point	Characteristic Value	Results
$A_1(0,0,0)$	$L+P-W(s), -C_2(-), R_5-C_5(s)$	stable point or saddle point
$A_2(1,0,0)$	$W-P-L(s), P-C_2-2C_1+S_1(s), R_5-C_5(s),$	unknown point
$A_3(0,1,0)$	$-S_1–W(-),\ C_2(+),\ R_5-C_4(s)$	saddle point
$A_4(0,0,1)$	$L+P–W(s),\ R_3-C_2(s),\ C_5-R_5(s)$	unknown point
$A_5(1,1,0)$	$S_1+W(+),\ 2C_1+C_2-P-S_1(s),\ R_5-C_4+S_2(s)$	saddle point or unstable point
$A_6(1,0,1)$	$W-P–L(s),\ P-C_2-2C_1+R_2+S_1(s),\ C_5-R_5(s)$	unknown point
$A_7(0,1,1)$	$-S_1-S_2–W(-),\ C_2-R_3(s),\ C_4-R_5(s)$	stable point or saddle point
$A_8(1,1,1)$	$S_1+S_2+W(+),\ 2C_1+C_2-P-R_2-S_1(s),\ C_4-R_5-S_2(s)$	saddle point or unstable point

4. Simulation Analysis

4.1. SD Model

The tripartite evolutionary game provides the theoretical foundation for system dynamics modeling, with the relationships between variables in the model explicitly defined by Equations (1)–(12). These equations determine the functional associations among cumulative variables, state variables, auxiliary variables, and external variables. The model incorporates three cumulative variables representing the probability distributions of government intervention strategies, enterprise implementation strategies, and consumer green consumption strategies. These cumulative variables govern three corresponding state variables, which quantify the rate of probability change in strategic adoption by governments, enterprises, and consumers, respectively. The six auxiliary variables are, respectively, the expected payoff of government management, the expected payoff of government non-intervention, the expected payoff of enterprise implementation, the expected payoff of enterprise non-implementation, the expected payoff of consumer green consumption, and the expected payoff of consumer non-green consumption. The external variables are explained in detail in Table 1. Within this framework, we employed Vensim PLE to construct a system dynamics model comprising three cumulative variables, three state variables, six auxiliary variables, and multiple external variables, as illustrated in Figure 3 [59,60].

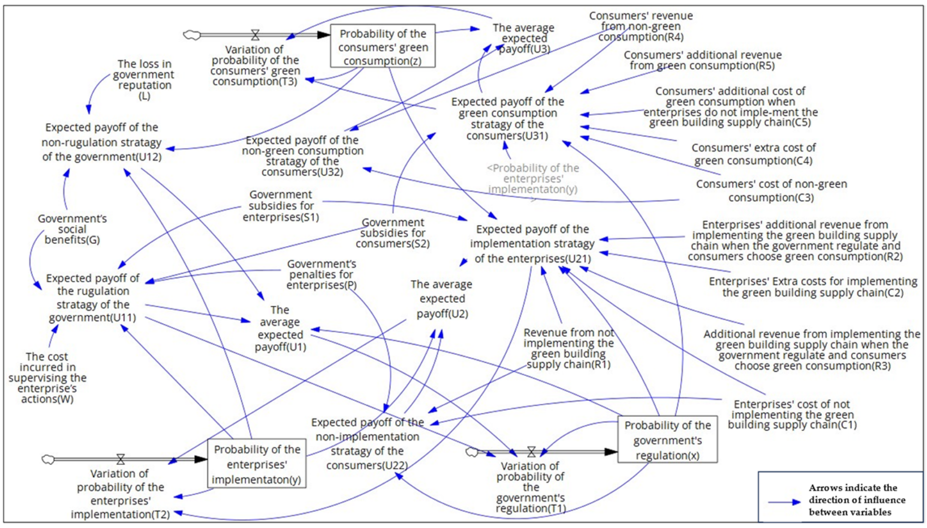


Figure 3. System dynamics model of the GBSC implementation.

Following the established evolutionary game framework and focusing on the government as a representative case, the key variables are U_{11}, U_{12}, and U_1; the following is derived:

$$T_1 = x(U_{11} - U_1) \tag{24}$$

The system dynamics simulation will be conducted using the following parameters: INITIALTIME = 0, FINALTIME = 300 weeks, and TIMESTEP = 0.0078125 weeks. Given the significant regional development disparities across China and acknowledging the inherent challenges in assigning precise values to the variables, this study focuses on analyzing the trends in strategy adoption by the government, enterprises, and consumers [61].

Regarding simulation parameter configuration, empirical measurement of certain parameters remains challenging. Existing research demonstrates that the advantage of the system dynamics model lies not in parametric accuracy but in the capacity to reveal behavioral patterns through dynamic interactions [62]. Aligned with this methodological perspective, our study focuses on analyzing the trend changes and driving factors in the strategic adoption of the government, enterprises, and consumers. To initialize parameters, this study employed the approach of Wang et al. and considered data from a green building industry research report [55,63,64]. This approach was chosen to ensure that the initial parameter values were grounded in established methods and relevant industry data; the specific assumed numerical values are shown below:

1. Initial value assumptions for government-related variables: W is set to 0.02; P is set to 0.1; S_1 is set to 0.6; S_2 is set to 0.6; G is set to 1; L is set to 1.
2. Initial value assumptions of enterprise-related variables: C_1 is set to 35; R_1 is set to 7; C_2 is set to 0.75; R_2 is set to 0.6; R_3 is set to 0.8.
3. Initial value assumptions of consumer-related variables: C_3 is set to 70; R_4 is set to 2; C_4 is set to 8; R_5 is set to 3; C_5 is set to 1.5.

The units for the model parameters, excluding the coefficients, are hundred yuan/m^2. To create an unbiased baseline scenario that avoids introducing any initial impact on a particular strategy, the initial probabilities of the tripartite parties' strategic choices, x, y, and z, are all assumed to be 0.5 [65].

4.2. Analysis of the Impact Mechanism of the Tripartite Strategy

4.2.1. Government Intervention Probability X

With the initial probability of government intervention (x) set to 0.5, and random initial probabilities assigned to the strategies of enterprises (y) and consumers (z), the resulting trajectory is shown in Figure 4a [66]. Under these conditions, the probability of government intervention decreases to and stabilizes at 0, indicating a clear preference for the non-intervention strategy. To isolate the individual effects of y and z on the probability of government intervention, the value of each variable was separately set to 0. The corresponding results are displayed in Figures 4b and 4c, respectively. These figures analyze the influence of individual enterprise and consumer strategies on the government's strategy by setting either y or z to 0. Specifically, when z is 0, the government still adopts the non-intervention strategy, which is consistent with the final outcome observed in Figure 4a. This suggests that variations in z, the probability of consumers' green consumption, have a relatively minor influence on the probability of government intervention. These variations primarily affect the speed of the government's intervention strategy evolution but not its final decision. Conversely, the probability of enterprises implementing the GBSC (y) has a more significant effect on determining the government's strategy.

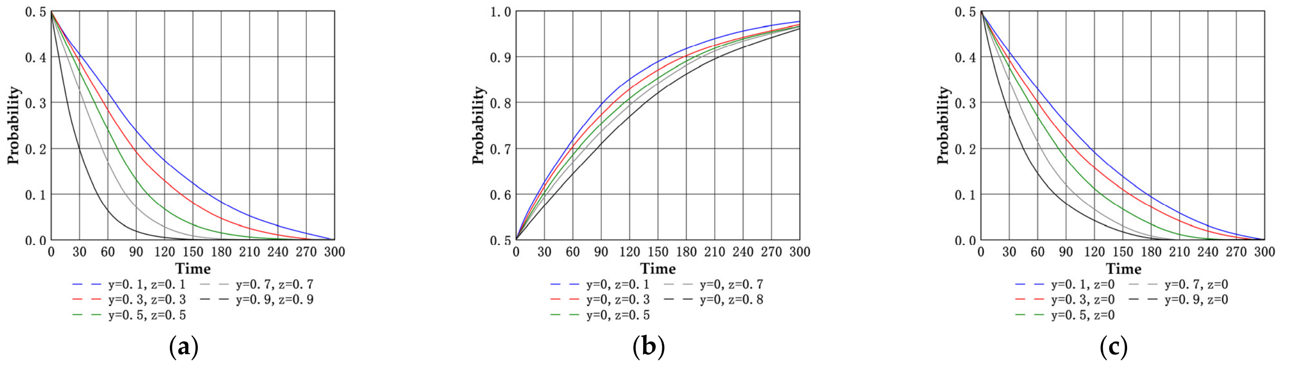
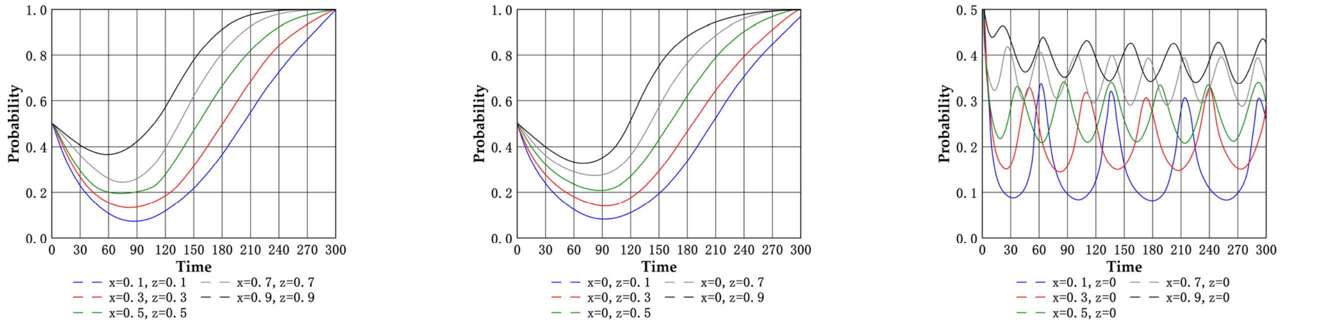


Figure 4. Effects of changes in initial value of y and z on the evolution of the government intervention probability x. (**a**) Randomly Select Initial Value of y and z; (**b**) Randomly Select Initial Value of z When $y = 0$; (**c**) Randomly Select Initial Value of y When $z = 0$.

4.2.2. Enterprises Implementation Probability Y

With the initial probability of enterprises implementing the green supply chain (y) set at 0.5 and random initial values assigned to government intervention (x) and consumer green consumption (z), the resulting trajectory is shown in Figure 5a. As depicted, the probability of enterprises adopting the strategy exhibits a non-monotonic trend, ultimately converging to 1. This indicates that enterprises will ultimately choose to implement the GBSC. To isolate the individual influences of x and z on the probability of enterprises implementing the strategy, the value of each variable was separately set to 0. The corresponding results are presented in Figure 5b,c. Specifically, when x is 0, the evolutionary trajectory of y is largely consistent with that observed in Figure 5a, where enterprises ultimately implement the GBSC. This suggests that the probability of enterprises adopting the strategy is primarily influenced by z, with minimal dependence on x. In other words, enterprise strategy is more responsive to consumer strategies than to government strategies. Conversely, when z is 0, the strategy choice of enterprises is solely driven by the government, resulting in the eventual adoption of a strategy not to implement the GBSC. Comparative analysis reveals that enterprises cannot achieve a stable equilibrium in implementing the GBSC solely through government intervention; rather, green consumption by consumers is the critical factor.

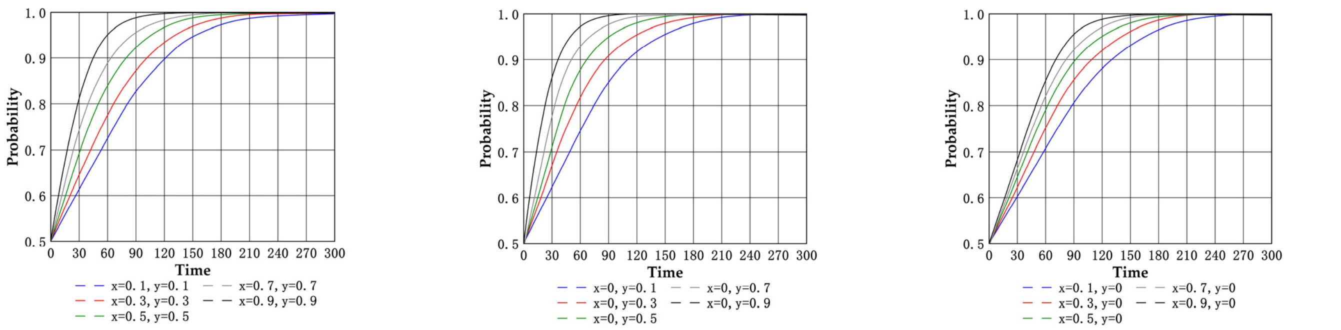


(**a**) (**b**) (**c**)

Figure 5. Effects of changes in Initial value of y and z on the evolution of the enterprise implementation probability y. (**a**) Randomly Select Initial Value of x and z; (**b**) Randomly Select Initial Value of z When x = 0; (**c**) Randomly Select Initial Value of x When z = 0.

4.2.3. Consumer Green Consumption Probability Z

With the initial probability of consumers adopting green consumption (z) set at 0.5, and random initial probabilities assigned to government intervention (x) and enterprise green supply chain implementation (y), the resulting dynamics are depicted in Figure 6a. The probability of consumers adopting green consumption (z) ultimately converges to 1, indicating that consumers will eventually choose the green consumption strategy. To isolate the individual effects of x and y on the probability of consumers adopting green consumption, the value of each variable was separately set to 0, with corresponding outcomes illustrated in Figure 6b,c. As these figures show, while the rate of z's evolution varies across the two scenarios, the final evolutionary outcome remains consistent with that observed in Figure 6a, converging towards green consumption. This suggests that both individual and joint green actions by enterprises and the government can effectively encourage green consumption. Consumer strategies are influenced by the interactions between government and enterprise strategies, with their concerted green initiatives ultimately driving consumers towards the adoption of green consumption practices.



(**a**) (**b**) (**c**)

Figure 6. Effects of changes in Initial value of x and y on the evolution of the consumer green consumption probability z. (**a**) Randomly Select Initial Value of x and y; (**b**) Randomly Select Initial Value of y When x = 0; (**c**) Randomly Select Initial Value of x When y = 0.

4.3. Stability Analysis of Pure Strategies

When the strategies chosen by the government, enterprises, and consumers are binary (represented by either 0 or 1), there are eight pure strategy combinations: $A_1(0,0,0)$,

$A_2(0,0,1)$, $A_3(0,1,0)$, $A_4(1,0,0)$, $A_5(0,1,1)$, $A_6(1,0,1)$, $A_7(1,1,0)$, and $A_8(1,1,1)$. If all three participants maintain their current strategies, the game will reach an equilibrium. However, if any participant deviates from its current strategy, the existing stable state will be disrupted. To investigate the evolution of the three participants' strategies, the initial values of these strategy combinations can be perturbed. For instance, the initial values for the simulation can be adjusted from $(0,0,0)$ to $(0.01, 0.01, 0.01)$, or from $(1,1,1)$ to $(0.99, 0.99, 0.99)$, allowing for the verification of the stability of these strategy points. Using the $(0,0,0)$ combination as an example, a slight perturbation of its initial value causes the system to evolve toward the $(0,1,1)$ strategy, as illustrated in Figure 7. Through verification, all eight pure strategy combinations ultimately converge with the (0,1,1) strategy. This demonstrates that, under the initial conditions established for this study, the tripartite evolutionary game model has a unique evolutionarily stable strategy (ESS) at (0,1,1). This ESS corresponds to a scenario where the government does not intervene, enterprises implement the GBSC, and consumers engage in green consumption. This result is consistent with the preceding stability analysis of the evolutionary game, further validating the model.

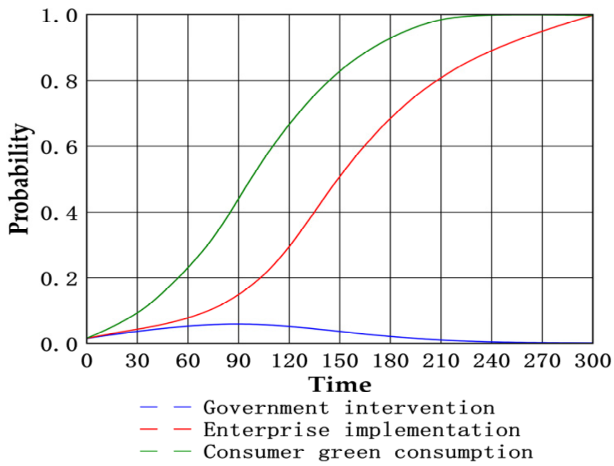


Figure 7. Evolution path of strategy combination $(0,0,0)$.

4.4. Mixed-Strategy Stability Analysis

To investigate mixed-strategy scenarios, we conduct a comparative analysis of cases with initial strategy probabilities set at higher (0.7,0.7,0.7) and lower (0.3,0.3,0.3) levels. To examine scenarios with mixed initial strategies, we analyze cases where the initial probabilities of the government, enterprises, and consumers adopting their respective strategies are set at both a higher level (0.7,0.7,0.7) and a lower level (0.3,0.3,0.3). When the initial probabilities are (0.7,0.7,0.7), substituting $x = 0.7$, $y = 0.7$, and $z = 0.7$ into the system dynamics model, the resulting evolutionary process is depicted in Figure 8a. The results indicate that the three participants' final stable equilibrium strategy converges towards (0,1,0.9). Conversely, when the initial probabilities are (0.3,0.3,0.3), substituting $x = 0.3$, $y = 0.3$, and $z = 0.3$ into the system dynamics model, the resulting evolutionary process is depicted in Figure 8b. The results show that the three participants' final stable equilibrium strategy approaches (0,1,1). This evolutionary process reveals that when enterprises and consumers have relatively low probabilities of implementing the GBSC and green consumption, their behavior tends towards non-implementation and conventional consumption. However, with the intervention of the government, the behavior of enterprises and consumers gradually evolves toward implementing the GBSC and purchasing green buildings. When enterprises all implement the GBSC and consumers fully engage in green consumption, the government's behavior evolves towards non-intervention. At this point, the three participants' strategies reach a final stable equilibrium.

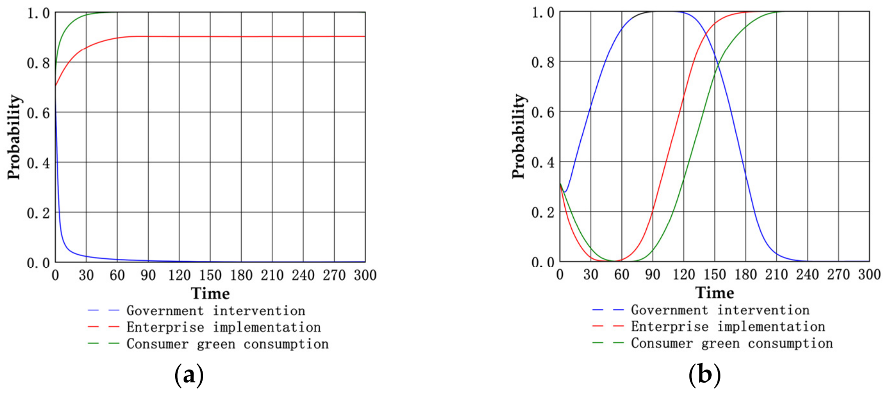


Figure 8. Evolution path of mixed strategy. (**a**) Evolution path of strategy combination (0.7,0.7,0.7); (**b**) Evolution path of strategy combination (0.3,0.3,0.3).

4.5. Sensitivity Analysis

The preceding research demonstrates that the stable equilibrium strategy of the tripartite evolutionary game model exhibits notable variations under different initial conditions. As the demand side of the terminal products of the green building supply chain, the behavior pattern of consumers has a crucial impact on the evolution path of the whole system. Therefore, the sensitivity analysis of this study focuses on the factors that affect consumers' green consumption.

Based on the stability analysis of the equilibrium point in Table 2, the value of the parameter setting can determine whether the strategy combination is an equilibrium point [55]. Thus, it can be concluded that exogenous variables that affect consumer strategy choice include the cost of non-green consumption C_3, the revenue from non-green consumption R_4, the extra cost of green consumption C_4, the additional revenue from green consumption, and R_5 the additional cost of green consumption when enterprises do not implement the GBSC C_5. To investigate the effect of parameter changes, the simulation model sets the initial probabilities of the government, enterprises, and consumers' strategic choices to 0.5.

Figure 9a,b demonstrate that variations in the initial values of the cost of non-green consumption C_3 and the revenue from non-green consumption R_4 have a relatively minor impact on the consumers' ultimate strategic choice. Consumers ultimately tend towards a green consumption strategy. However, the rate of consumer adoption of a green consumption strategy is indeed sensitive to changes in C_3 and R_4. As illustrated in Figure 9a, higher values of C_3 correlate with a slower rate of green consumption at any given simulation point. Conversely, Figure 9b demonstrates that increasing R_4 accelerates the rate of green consumption.

Figure 9c shows the impact of C_4 on consumers' strategy choices. This part examines the dynamic process of consumers' strategic evolution when C_4 is set to 6, 8, 10, 12 and 14, respectively. When the price gap between green buildings and non-green buildings is relatively low, consumers demonstrate a higher propensity to engage in green consumption. Conversely, when the value of C_4 increases to 10, the probability of consumers' green consumption strategy is stable at 0.6. When the value of C_4 increases to 12, the strategic choices of consumers tend to opt for non-green consumption. This suggests that excessively high green product premiums will significantly suppress consumers' willingness to engage in green consumption. Therefore, the extra cost of green consumption C_4, as a sensitive parameter affecting the green decisions of consumers, requires judicious control for the effective implementation of the GBSC.

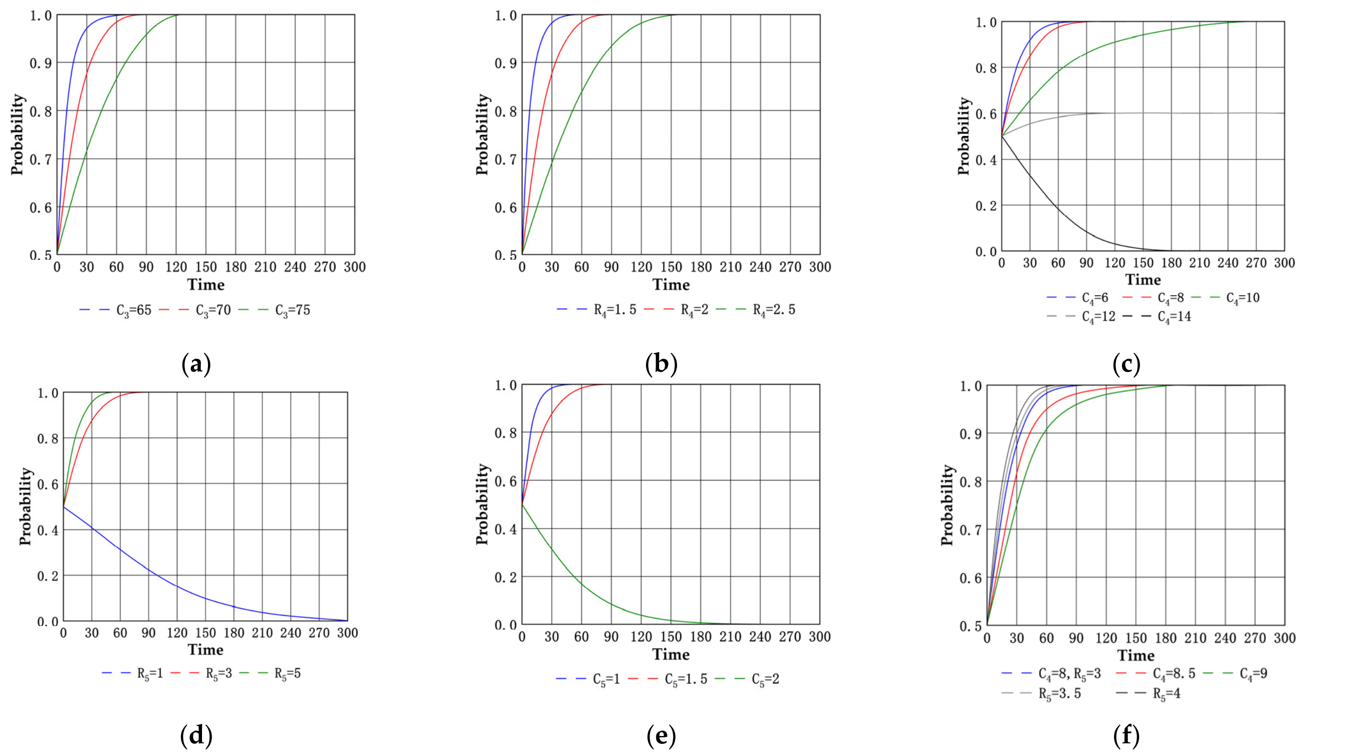


Figure 9. (**a**) Impact of C_3 on consumer strategy selection; (**b**) Impact of R_4 on consumer strategy selection; (**c**) Impact of C_4 on consumer strategy selection; (**d**) Impact of R_5 on consumer strategy selection; (**e**) Impact of C_5 on consumer strategy selection; (**f**) Impact of R_4 and R_5 on consumer strategy selection.

In Figure 9d, the impact of R5 on consumer strategy selection is depicted. The additional benefits of consumers' green consumption R_5 primarily manifest as the environmental protection utility derived from green consumption, with its initial value set to 3. Recognizing the heterogeneity in consumers' perceptions of environmental value and green effectiveness, this paper categorizes consumers into three groups: those with low, moderate, and high green preferences. It is posited that the higher the degree of consumers' green preference, the stronger their perception of green effectiveness and the greater the environmental protection utility derived from green consumption, making them more likely to adopt green behaviors. These three consumer types correspond to R5 values of 1, 3, and 5, respectively, and the strategic evolution of consumers is illustrated in Figure 9d. As depicted in Figure 9d, when consumers exhibit moderate or high green preferences (i.e., R_5 is 3 and 5, respectively), they tend to adopt the green consumption strategy. However, when consumers have low green preferences, they tend toward the non-green consumption strategy. To effectively promote green consumption by consumers, it is necessary to focus on enhancing consumers' perception of the environmental protection utility derived from green consumption.

Figure 9e shows the impact of C_5 on consumers' strategy choices. C_5 represents the consumer's additional cost of green consumption when enterprises do not implement the GBSC, for instance, the extra costs associated with proactively selecting green building materials and independently installing new ventilation systems. From the evolutionary path in the figure, it can be concluded that when C_5 increases to 2, consumers will shift to non-green consumption. Even when companies do not provide green building products, consumers' adoption of a green consumption strategy remains affected by extra costs.

Figure 9f depicts the impact of the extra cost of green consumption and the additional revenue from green consumption on consumers' strategy choices. According to the preceding analysis, we conclude that additional costs and benefits significantly influence consumers' adoption of the green consumption strategy. Based on the difference in the evolutionary trajectories of consumers' green consumption probability shown in Figure 9f, we can conclude that: the marginal effects of the extra cost of green consumption are more significant, while the marginal impacts of the additional revenue from green consumption are smaller. Therefore, it is more effective to decrease the price gap of green buildings by designing corresponding policies and measures.

5. Conclusions

5.1. Findings

This study innovatively investigates the equilibrium dynamics of GBSC implementation through an integrated analytical framework combining evolutionary game theory and system dynamics. Departing from conventional research paradigms, we developed a tripartite evolutionary game model under bounded rationality assumptions, encompassing the government, enterprises, and consumers. The paper establishes tripartite evolutionary strategies and employs system dynamics methods to validate stable strategies and influence mechanisms among participants. Furthermore, a comprehensive analysis of pure and mixed strategies and key influencing factors was conducted through scenario simulations and sensitivity testing. The enhanced findings and implications are as follows:

1. The participants within the GBSC exhibit significant interdependence. Specifically, government intervention is primarily driven by enterprises' implementation of green supply chains; enterprises' willingness to implement the green supply chains is primarily driven by consumers' green consumption; and consumers' green consumption is influenced by the combined efforts of the government and enterprises.
2. Under different initial strategy scenarios, when government intervention intensifies to a critical threshold, it effectively promotes the implementation of the GBSC by enterprises and green consumption by consumers. However, exceeding this intensity of critical intervention, while increasing returns for enterprises and consumers, will decrease government returns, leading to reduced intervention efforts. In the early stages of GBSC development, differing initial strategies result in heterogeneity in the strategic choices of participants. However, as the supply chain matures, the tripartite game system converges towards a stable equilibrium at (0,1,1), evolving toward a state where government intervention is unnecessary, enterprises actively implement the GBSC, and consumers engage in green consumption.
3. Through the sensitivity analysis of consumer-related parameters, it is known that: The extra cost of green consumption and the perceived environmental protection benefits are key determinants influencing the green consumption strategies of consumers. Excessively high green building premiums will deter consumers from opting for green consumption, while a weak perception of environmental benefits will cause moderately green-inclined consumers to opt for non-green consumption. The marginal effects of the extra cost of green consumption are more significant, while the marginal impacts of the additional revenue from green consumption are smaller. Therefore, when formulating policies, the government can consider enhancing consumers' awareness of environmental benefits, and at the same time, reducing the additional cost of green consumption for consumers.

5.2. Discussion

Through the analysis of tripartite evolutionary game and system dynamics, this study finds the interdependence between participants: government intervention responds to firm actions, firm strategy is consistent with consumer behavior, and consumer choice depends on the joint efforts of the government and firm. Our tripartite model extends the previous binary analysis, with Liu et al.'s work focusing on government-business interactions [67]. Notably, convergence to a stable equilibrium (0,1,1) suggests that the government has finally withdrawn from intervention, contrary to the continuous intervention advocated by Sun et al. [68]. Furthermore, the dual reliance of consumers on government and corporate behavior is consistent with Feng et al. [69].

Sensitivity analysis emphasizes that consumer behavior strategies are more sensitive to the additional costs of green consumption than to the perceived environmental benefits, a finding consistent with Kahneman's loss avoidance principle in behavioral economics [70]. The research of Zhang et al. emphasizes that information asymmetry is the main obstacle to green consumption, and our findings suggest that cost reduction may have more impact than green propaganda campaigns alone [71]. Our study identified a moderating effect of environmental benefit perception. This finding suggests that a mixed policy, combining cost subsidies and initiatives to enhance consumers' environmental perception, can jointly increase the probability of green consumption. This proposition is supported by the behavioral promotion experimental evidence of Yang et al. [72].

5.3. Recommendations

1. Establish a Collaborative Governance Framework

This study reveals the triple coupling relationship between government intervention, business practice, and consumer behavior in the green building supply chain (GBSC): the effectiveness of government intervention depends on the green processes of enterprises, the driving force of enterprise transformation comes from the green demand of consumers, and the decisions of consumers are influenced by the synergistic effect of government and enterprise. In order to strengthen this synergistic effect, it is suggested to build a data-driven tripartite collaborative governance framework. A priority for this framework should be the establishment of a unified, open data platform, integrating information on government policies, enterprises' green supply chain performance, and consumer feedback. Data analysis can be leveraged to dynamically adjust government incentives and regulations. Furthermore, it can guide enterprises in innovating green building technologies and materials, and provide consumers with transparent information about green building products. In addition, the platform should facilitate direct communication and feedback loops among the three parties, enabling the continuous improvement and adaptation of GBSC policies and practices. By leveraging data analysis and promoting open communication, this collaborative framework can effectively foster the sustainable development of the green building industry.

2. Implement Dynamic Regulation Mechanisms

Through analysis, this study concludes that under ideal conditions, the three-party game system tends to be stable and balanced at (0,1,1), evolving to a state where the government does not need supervision, enterprises actively implement GBSC, and consumers carry out green consumption. The system ultimately converges with stable equilibrium states where active enterprise participation and consumer green consumption sustain GBSC operations with reduced regulatory intervention. The optimal scenario envisions the eventual cessation of government subsidies, reflecting a hands-off approach. However, to address the possibility of market inefficiencies, the government could retain a limited regulatory presence. To facilitate the sustainable expansion of the GBSC, policymakers might adopt intertemporal policy coordination, strategically combining substantial short-term subsidies with sustained initiatives to educate consumers on the benefits of green consumption. This integrated strategy seeks to minimize reliance on subsidies over time and foster self-sustaining green demand within the GBSC system. At the same time, the government can establish a dynamic subsidy model, adopt a step subsidy retreat, and gradually reduce the dependence of enterprises on subsidies.

3. Optimize Consumption Incentive Structure

In the sensitivity analysis, we divided consumer groups according to different levels of green preference. Different regions may have different acceptance of green buildings due to economic levels, cultural concepts, policy environments, and other factors. Policy recommendations may require differentiated strategies, such as promoting high-end green products in high-income areas and providing subsidies or educational outreach in low-income areas. According to the analysis, the additional cost of green consumption and the perceived environmental protection benefits are key determinants influencing the green consumption strategies of consumers. The government can implement a dual policy approach. From the consumer perspective, a mandatory "carbon footprint visualization" labeling system could be promoted, enabling consumers to directly assess the lifecycle emission reduction benefits of green buildings. Simultaneously, the government and enterprises can jointly limit the premium for green buildings to an acceptable percentage above the price of conventional buildings and provide targeted subsidies for costs exceeding this limit. Sensitivity analysis revealed that the marginal effects of the extra cost of green consumption are particularly significant, suggesting this should be a key focus of policy interventions. Given that enterprises may face challenges such as high initial investments, financing difficulties, and long payback periods in the early stages of supply chain transformation, unilateral cost reduction by businesses is often unrealistic. Therefore, policies should not only provide subsidies but also support joint government-enterprise investment in research and development to share costs and reduce the overall expenses associated with promoting green building supply chains. This collaborative approach is more likely to effectively reduce the perceived extra cost of green consumption for consumers.

5.4. Limitations

This study combines evolutionary game theory with system dynamics to provide theoretical and practical contributions to green building supply chain governance. This paper still has some limitations.

First of all, although this study includes consumer green preference and analyzes its impact on the implementation decisions of governments, enterprises, and consumers in the GBSC, the complexity of the GBSC in reality determines that it involves many stakeholders. Future research may consider including more game players, carrying out more detailed divisions, and carrying out multi-party games, so as to more comprehensively reveal the operation mechanism of the GBSC. Secondly, the model treats firms and consumers as homogenous groups, ignoring the heterogeneity of enterprises' sizes and the regional differences of consumers. In future research, the sizes of enterprises and consumer regions will be more carefully divided. Thirdly, although system dynamics simulations align with theoretical predictions, the lack of empirical data from transitioning GBSCs limits the external validity verification. If we can increase the sample size and enrich the data sources, it will help to simulate and analyze the tripartite game relationship more accurately.

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