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Research on System Optimization and Decision-Making for Building Industrialization Chain Focused on Carbon and Waste Reduction

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Abstract

Aiming at the "dual carbon" goals, this paper treats the industrial chain of building industrialization as a complex system and focuses on the synergistic reduction of carbon and waste. By analyzing the key contradictions within the system, a multi-dimensional indicator system encompassing policy drivers, technical capabilities, and environmental performance is constructed. An evolutionary game model between the government and core enterprises is then established to explore their strategic interaction mechanisms. Simulation results show that under current parameters, the system stabilizes in a "regulatory dilemma" state of "strict government supervision and traditional enterprise practices," revealing that excessively high transformation costs are the key bottleneck suppressing market-driven dynamics. Sensitivity analysis further identifies a priority sequence for breaking the dilemma: the primary task is to significantly reduce transformation costs, followed by establishing synergistic incentives combining subsidies and long-term benefits, while punitive mechanisms primarily serve as a safety net. Based on this, the study proposes a collaborative decision-making system from a system optimization perspective, prioritizing cost reduction, with incentives as the core and supervision as the safeguard, providing theoretical foundations and pathways for advancing the green and low-carbon transformation of the building industrialization industrial chain.

Keywords

Construction industrialization; System optimization; Evolutionary game theory; Carbon emission reduction; Construction waste; Regulatory dilemma

1. Introduction

In the final year of the 14th Five Year Plan and during the planning period of the 15th Five Year Plan, the "dual carbon" strategy remains a rigid constraint for the construction industrialization industry, as well as a key path for the transformation and upgrading of the construction industrialization industry chain and the realization of green construction.

This article is based on system optimization and decision theory, treating the industrial chain as a whole, and studying how to achieve collaborative reduction of carbon and waste through optimizing decision guidance systems.

At present, a clear policy framework has been established at the national level to promote the green and low-carbon transformation of the construction industry. This framework revolves around the two core areas of "energy conservation and carbon reduction" and "waste management", setting clear quantitative goals and development paths[1-2].In terms of construction methods, policies strongly guide the industry to transform towards a new type of construction industrialization represented by prefabricated buildings, and set a specific goal of achieving a 40% proportion of prefabricated buildings in new construction by 2030[1]. At the same time, by promoting intelligent construction, integrated building photovoltaics, and ultra-low energy buildings, the aim is to fundamentally change the traditional high consumption and high emission construction mode[2].

In terms of source reduction and process control, the policy system emphasizes the implementation of energy-saving and carbon reduction standards for new buildings and the widespread application of green building materials, and sets higher thresholds for energy efficiency and environmental protection access in the production of high energy consuming building materials such as cement and glass[2].For existing buildings with large inventory and high energy consumption, we will systematically promote energy-saving and equipment upgrades by combining urban renewal with the renovation of old residential areas, in order to improve overall energy efficiency[2].This series of measures together constitute the entire process of carbon emission reduction management strategy from supply to demand, from new construction to stock.

Equally important as carbon reduction is the improvement of the construction waste management system. The national goal is to achieve an average resource utilization rate of over 50% for construction waste in prefecture level and above cities by 2027[3]. To achieve this goal, the policy has established a full chain governance plan from the source to the end: at the source, promote green construction and prefabricated construction to suppress waste generation, and implement strict classification and treatment; In the transportation process, strict prevention of secondary pollution is achieved through technical standards and behavioral supervision; On the disposal side, scientific planning of resource utilization facilities, promotion of the application of recycled building materials products, and improvement of market mechanisms based on the principle of "whoever generates, pays" are adopted to open up the "last mile" of turning construction waste into treasure[3].

However, despite the increasingly sophisticated top-level design, the construction industrialization industry chain still faces systemic challenges in moving towards green and low-carbon practices[1-3]. The core contradiction lies in the lack of an effective balance and incentive compatibility mechanism between the private costs borne by enterprises in green transformation and technological upgrading and the ecological and environmental benefits obtained by society, resulting in insufficient endogenous market power. Therefore, this article regards the construction industrialization industry chain as a complex system, focusing on the collaborative reduction of carbon and waste. By constructing a systematic analysis model, it explores the decision-making interaction and system evolution path among various subjects in the industry chain, in order to seek optimization strategies to solve the current dilemma and provide decision-making references for promoting the overall optimization and sustainable development of the industry chain.

2. Diagnosis of key issues in the industrial chain system

Based on the policy background described in this article, analyzing the construction industrialization industry chain as a closed-loop system from "building material production, component prefabrication, assembly construction" to "operation, maintenance, and demolition recycling" reveals that it faces several deep-seated systemic problems in achieving the goal of carbon and waste reduction. These problems have severed the organic connections between various links in the industrial chain, becoming bottlenecks that restrict its green and low-carbon transformation.

Firstly, there is a dual lock-in between high carbon path dependence and green supply costs in the front-end of the system. The core issue lies in the excessively high premium rate of low-carbon building materials. The production of building materials in the upstream of the industrial chain, especially in the fields of cement, glass, etc., still heavily relies on fossil fuels for its technological route, resulting in a lack of competitiveness in the price of green building materials. Downstream architectural design and construction companies are constrained by project cost pressures, lacking sufficient subsidy intensity and implementation rate guarantees, and lacking economic incentives to actively select green components, making it difficult to form a virtuous cycle between low-carbon supply and market demand.

Secondly, the system operation process exhibits typical characteristics of fragmented links and insufficient collaboration. The traditional linear model of "design production construction" has not been completely broken, manifested by low standardization rate of prefabricated components, insufficient depth of BIM technology application, and weak collaborative ability of industry chain data. This leads to a wide variety of prefabricated component types, making it difficult for production lines to achieve economies of scale. This not only increases production costs, but also directly causes high material and energy losses during the construction phase, ultimately resulting in high carbon emissions per unit area and construction site waste.

Finally, it is difficult to effectively form a closed-loop loop at the end of the system. Although policies have set clear targets for the utilization rate of construction waste resources and the proportion of recycled aggregates, under the current market mechanism, responsible parties often prefer to choose the lowest cost landfill disposal. The fundamental reason is that the product standards, application channels, and market recognition of recycled building materials are still insufficient, which makes it difficult to realize the value of resource-based products and cannot bring significant economic benefits to projects that adopt these products, thereby suppressing the enthusiasm of social capital to enter this field.

In summary, the cost-benefit imbalance centered on the premium rate of low-carbon building materials, insufficient process collaboration represented by data collaboration capabilities, and the lack of a circular mechanism characterized by the rate of construction waste resource utilization all constitute the core obstacles to achieving sustainable development in the current construction industrialization industry chain. To solve this system dilemma, it is urgent to establish a decision analysis framework that can quantify these key indicators and coordinate the interests of all parties.

3. Construction of System Performance Indicator System and Game Model

3.1. Construction of System Performance Indicator System

To accurately diagnose and solve the above system problems, this article constructs a system performance indicator system covering three dimensions: "drive capability performance". This system aims to transform abstract system problems into quantifiable, monitored, and optimizable key performance indicators, providing a quantitative foundation for subsequent game modeling and simulation.

（1）Policy and market driven dimensions

- Subsidy intensity: The government's unit area subsidy for green building projects (yuan/m^2) is a direct economic lever to incentivize enterprise transformation [4-5].
- Subsidy implementation rate: The percentage (%) of actual subsidy funds disbursed to the total planned subsidy, reflecting the credibility and implementation efficiency of the policy [4-5].
- Minimum prefabrication rate: The proportion (%) of prefabricated components required by regulations is a reflection of the government's administrative supervision efforts [6-7].

（2）Dimension of Technical and Management Capability

- Standardization rate of prefabricated components: the proportion of the number of standard components used to the total number of components (%), measuring the basic level of industrial chain collaboration [8-9].
- BIM Technology Application Depth Index (Non dimensional Index): Evaluating the Application Stages and Value of BIM Technology throughout the Project Lifecycle [10-11].
- Industrial chain data collaboration capability index (dimensionless index): measures the efficiency of data exchange and business collaboration between design, production, construction and other links [10,12].

（3）Dimensions of Environmental and Resource Performance

- Carbon emissions per unit area: the amount of carbon dioxide emissions generated during the construction phase of a building (kgCO_2/m^2) [13].
- Full life cycle carbon emission intensity: the total carbon emissions of buildings

from building material production to demolition and recycling (kgCO $_2$/m²) [14-15].

- Resource utilization rate of construction waste: the proportion of construction waste that has been resource utilized to the total emissions (%) [3].
- Proportion of recycled aggregate usage: In materials such as concrete, the proportion of recycled aggregate replacing natural aggregate (%) [16-17].

3.2. Government enterprise evolutionary game model

（1）Basic assumptions and parameter settings of the model

- To solve the problem of inconsistent multi index scalar classes, this article adopts the method of setting benchmark values and standardizing them. Convert all parameters into dimensionless values in the [0,1] interval, with a benchmark value set at 0.5.
- Government Strategy Set: {Strict Regulation, Loose Regulation}, Enterprise Strategy Set: {Active Transformation, Maintaining Tradition}.

（2）Core parameter definition and standardization

The model parameters are mainly derived from the indicator system constructed in Section 3.1, and have been mapped and standardized, as shown in Table 1：

Table 1. Definition and benchmark values of key parameters

Parameter	Meaning (Mapping with Realistic Indicators)	Benchmark value and range of values
S	The government subsidy intensity combines the "subsidy intensity" and "subsidy implementation rate".	Benchmark value0.3， range [0,1]
F	The government's punishment intensity is linked to the regulatory requirement of "mandatory prefabrication rate".	Benchmark value0.5， range [0,1]
C_g	Government regulatory costs, including all administrative costs such as monitoring, verification, and law enforcement.	Benchmark value0.5， range [0,1]
C_e	The cost of enterprise transformation is determined by the "premium rate of low-carbon building materials" and is influenced by the "standardization rate" and "data collaboration capability".	Benchmark value0.75， range [0,1]
R_e	Long term benefits of enterprise transformation, including market reputation, carbon quota savings, and future policy dividends.	Benchmark value0.25， range [0,1]
R_g	The government's social benefits are positively correlated with achieving performance goals such as "carbon emissions per unit area" and "construction waste resource utilization rate".	Benchmark value0.8， range [0,1]
L	Corporate reputation loss, market, credit, and policy risks faced due to non transformation.	Benchmark value0.4， range [0,1]

The benchmark values for the above parameters are mainly based on qualitative judgment of the industry status and consideration of the convenience of model analysis. The core purpose is to construct a logical model that reflects the relative relationships between various forces in the real system, rather than making precise numerical predictions. The relative size between parameters (such as transformation cost Ce significantly higher than transformation benefit Re) reflects the core contradiction currently faced by enterprises. Subsequent analysis will indicate that the evolution trend and policy implications of the model are not sensitive to the specific values of these benchmark values and have good robustness。

（3）Construction of income matrix

Based on the above parameters, construct a revenue matrix for the government and enterprises, as shown in Table 2：

Table 2. Government and enterprise revenue matrix

Governmen \ Enterprise	Actively transforming (y)	Maintain tradition (1-y)
Strict supervision (x)	R_g-C_g-S，R_e-C_e+S	R_g-C_g+F，-C_e-F-L
Loose regulation (1-x)	R_g-S，R_e-C_e+S	-L_g，-L

In the revenue matrix, Lg represents the reputation or performance loss suffered by the government due to inadequate regulation resulting in the failure to achieve environmental and social goals. It is set as a fixed value (such as Lg=0.2) in the baseline scenario to reflect its secondary position relative to the core policy revenue Rg.

The establishment of the income matrix in this article marks the transformation of the complex real-world industrial system problems into a computable and analyzable dynamic evolutionary game model. This model clearly depicts the strategic interaction and balance of interests between the two core entities of the government and enterprises in a specific policy environment, laying a solid foundation for the next section to conduct in-depth simulation analysis of the system evolution path and explore the decision-making leverage of key parameters.

4. Model simulation and decision analysis

4.1. Copy dynamic equation derivation and simulation settings

The core of evolutionary game analysis lies in solving the replicative dynamic equations of the system to reveal the evolutionary path of government and corporate strategic choices. Firstly, it is necessary to calculate the expected returns of all parties based on the income matrix.

The expected return for the government's choice of "strict regulation" (x) is U_{g1}, the expected return for choosing "loose regulation" $(1-x)$ is U_{g2}, and the average expected return for the government is $\bar{U}_g$.

$$U_{g1} = y(R_g - C_g - S) + (1-y)(R_g - C_g + F)$$
$$U_{g2} = y(R_g - S) + (1-y)(-L_g)$$
$$\bar{U}_g = xU_{g1} + (1-x)U_{g2}$$

Similarly, assuming that the expected return of a company choosing "active transformation" (y) is U_{e1}, the expected return of choosing "maintaining tradition" $(1-y)$ isU_{e2}, and the average expected return of the company is $\bar{U}_e$.

$$U_{e1} = x(R_e - C_e + S) + (1-x)(R_e - C_e + S) = R_e - C_e + S$$
$$U_{e2} = x(-C_e - F - L) + (1-x)(-L)$$
$$\bar{U}_e = yU_{e1} + (1-y)U_{e2}$$

Based on this, a replication dynamic equation for the system is constructed, which describes the rate of change of the strategy ratio over time：

The government's replication dynamic equation：

$$F(x) = \frac{dx}{dt} = x(U_{g1} - \bar{U}_g) = x(1-x)(U_{g1} - U_{g2})$$

The dynamic equation of enterprise replication：

$$F(y) = \frac{dy}{dt} = y(U_{e1} - \bar{U}_e) = y(1-y)(U_{e1} - U_{e2})$$

Simulation setting: To explore the dynamic evolution law of the system, this study uses numerical simulation methods to solve the above differential equation system. The initial state of the system is set to (x, y)=(0.5, 0.5), where both the government and the enterprise choose their strategies with equal probability to simulate an initial situation without a dominant strategy. The benchmark parameter set adopts the settings of the third part (Ce=0.75, Re=0.25, S=0.3, F=0.5, Rg=0.8, Cg=0.5, L=0.4, Lg=0.2).

4.2. Benchmark scenario simulation and equilibrium analysis

Simulations were conducted under benchmark parameters, and the evolution trajectory of the system is shown in Figure 1, clearly indicating its stable convergence to the equilibrium point (0.97, 0.01). This means that the stable strategy for the evolution of the system is {strict government regulation, enterprises maintaining tradition}, which is a typical 'regulatory dilemma' model.

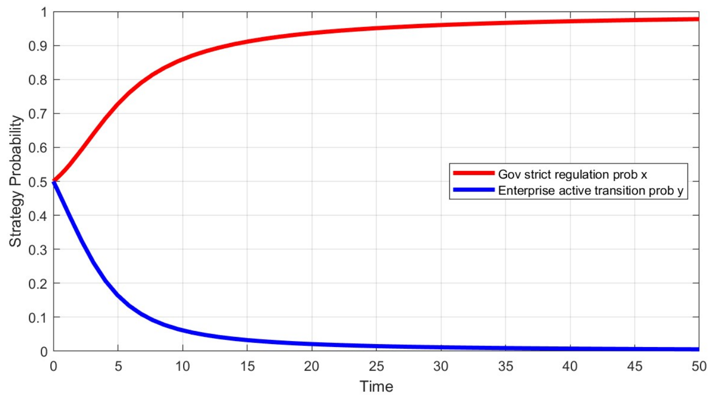

Figure 1. Evolutionary Trajectories of Government and Corporate Strategies

Based on the simulation results, which are highly consistent with the diagnosis of the current industry situation in this article, the core contradiction of the green transformation of the current construction industrialization industry chain has been empirically verified. The model shows that due to the significant increase in transformation costs (Ce=0.75) compared to the sum of transformation benefits and subsidies (Re+S=0.55), enterprises choose to "maintain tradition" as their dominant strategy under rational decision-making. In response, the government had to continue investing high regulatory costs (Cg=0.5) in an attempt to push for emission reduction targets, ultimately resulting in an inefficient lock-in state where the government was exhausted from regulation and companies passively responded. The benchmark scenario result is not a model failure, but accurately depicts the substantial lack of incentive mechanisms caused by cost-benefit imbalance in the real industrial system, providing a key benchmark and optimization starting point for exploring breakthrough paths in the future.

4.3. Sensitivity analysis and optimization decision-making

According to the simulation analysis of the benchmark scenario mentioned earlier, the system is deeply locked in a "regulatory dilemma". To explore feasible paths to solve this dilemma and identify effective policy intervention levers, this section conducts a systematic sensitivity analysis of key parameters.

（1）The Stubbornness of System Lockdown: The Dominant Effect of Transition Costs (Ce) Simulation shows (see Figure 2) that Ce has a dominant influence on the system state. When Ce is within a wide parameter range of 0.65 to 0.85, the system stubbornly stays in a "regulatory dilemma" state and does not transition to an ideal state. This reveals the depth and stubbornness of the current system's locked state, which means that small cost reductions are difficult to shake the existing pattern and must rely on strong external intervention.

Management insights: Resolving the dilemma requires fundamental measures that combine "pressure reduction" and "open source". It is necessary to reduce core costs such as the "low-carbon building material premium rate" below the critical point through strong technological innovation and industrial synergy; At the same time, public policies need to focus on building a cost sharing and compensation mechanism that covers the entire chain, fundamentally reversing the negative economic incentives for transformation.

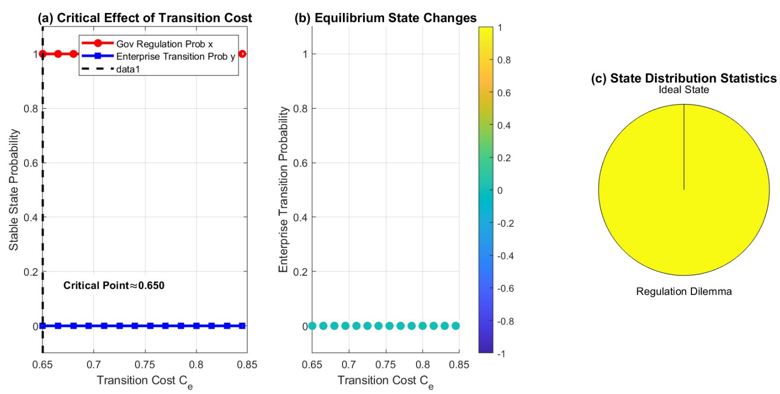

Figure 2. Analysis Diagram of the Impact of Transformation Cost (C_e) on System Equilibrium

（2）Collaborative breakthrough of policy tools: enhancing transformation benefits (Re) and optimizing subsidies (S)

The synergy analysis (Figure 3) reveals that under the current high cost structure, a single subsidy or revenue increase is difficult to drive the system out of the predicament. The heatmap shows that the ideal "safe zone" accounts for 0%, indicating that at the benchmark level of Ce=0.75, the synergistic effect of Re and S is suppressed by high costs and cannot function independently. However, cross-sectional analysis indicates that once the transformation cost is effectively reduced through other means, the synergistic driving effect of Re and S will be significantly enhanced, becoming the key to maintaining the ideal state.

Management inspiration: Policy design must have systematicity and temporality. In the short term, subsidies (S) should serve as a "starter" and act precisely to lower the actual threshold for transformation; In the medium to long term, it is necessary to cultivate a green consumption market, open up carbon trading channels and other mechanisms to effectively enhance the long-term market returns (Re) of enterprise transformation, and form a sustainable incentive mechanism with "market returns as the mainstay and financial subsidies as the supplement".

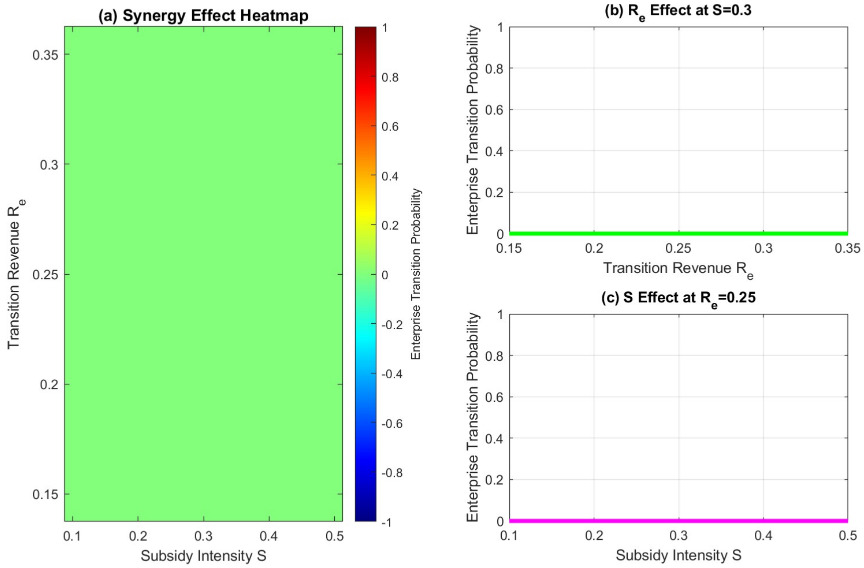

Figure 3. Synergy effect and cross-sectional analysis diagram of benefits and subsidies

（3）The bottoming role of regulatory rules: the protective value of punishment mechanism (F)

Simulation results (Figure 4) show that in unfavorable scenarios with high transition costs (Ce=0.8), the protective effect of punishment mechanism F is limited. Even if the punishment force F is increased to 0.95, it still fails to guide the system out of the predicament. This confirms the management principle of "insufficient incentives, regulatory failure" - when the economic cost of complying with rules is too high, the deterrent power of punishment will sharply weaken. However, the value of its' key stand'lies in providing guarantees for the effectiveness of other policy tools and preventing the system from sliding towards a worse equilibrium.

Management inspiration: The role of the government should be clearly defined as the "guardian of the bottom line of rules". Establishing clear, stable, and severe punishment mechanisms (F) is the cornerstone of building policy credibility. Its core value lies in setting "red lines", curbing speculative behavior, clearing obstacles for the establishment and operation of market mechanisms, and ensuring that other economic incentive policies can take effect within safe boundaries.

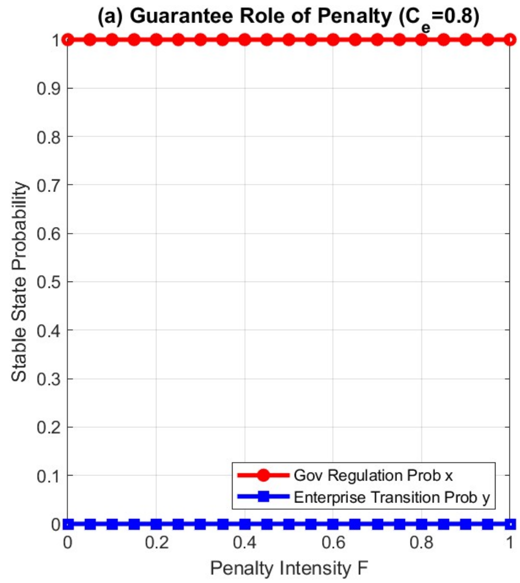

Figure 4 (a). The protective effect diagram of punishment mechanism under different C_e

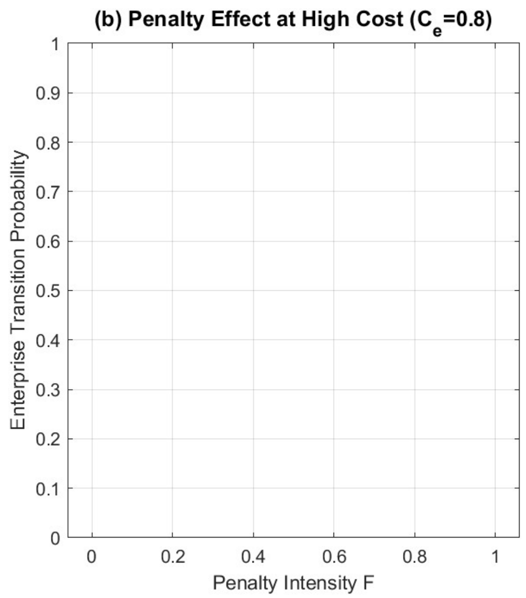

Figure 4 (b). Threshold effect diagram of punishment intensity under high cost

5. Suggestions for system optimization decision-making

To achieve the core goal of " Carbon and waste reduction " and promote the green and low-carbon transformation of the construction industrialization industry chain, it is necessary to implement a set of precise and coordinated system optimization decisions based on simulation conclusions. The decision-making system should strive to guide the evolution path of the system from the "regulatory dilemma" to the ideal state of "market dominance", and ensure that key environmental performance indicators such as carbon emission intensity and construction waste resource utilization rate are continuously improved.

The primary measure is to focus on carbon reduction and waste reduction in key areas, and strongly break through cost lock-in. Simulation shows that transformation cost (Ce) is the most sensitive parameter of the system. The government and industry alliances should prioritize targeting the production and prefabrication of building materials and components with the highest carbon footprint and waste output, allocate targeted research and development resources, overcome low-carbon/zero carbon building materials processes, and reduce design redundancy and construction cutting waste from the source by promoting standardization of prefabricated components. This move aims to simultaneously reduce the premium rate of low-carbon building materials and the material and energy consumption per unit product, laying the foundation for overall carbon reduction and waste reduction in the industrial chain.

Secondly, it is necessary to establish a "subsidy benefit" collaborative incentive system guided by environmental performance. The distribution of financial subsidies (S) should be forcibly linked to the measured indicators such as carbon emissions per unit area and construction waste resource utilization rate of the project, to ensure that funds accurately drive the improvement of environmental benefits. At the same time, accelerate the establishment of a carbon footprint accounting and certification system for recycled building materials products, and incorporate it into the scope of green building evaluation and carbon market trading, so that enterprises can obtain tangible market benefits (Re) in reducing carbon emissions throughout the entire industry chain and promoting waste resource utilization, forming an endogenous driving force for green development.

Finally, improve and establish a regulatory bottom line based on carbon and waste control goals, and strengthen institutional safeguards. The core of regulation should shift from process control to result control, upgrading traditional indicators such as "minimum prefabrication rate" to rigid constraints on the total carbon emissions and final landfill rate of the entire project lifecycle. The deterrent power of the punishment mechanism (F) should be reflected in the adherence to such environmental red lines, clearing obstacles for the effective driving of the "carbon and waste reduction" goals by the aforementioned economic incentive policies, and ultimately building a new pattern of industrial chain governance with clear goals and compatible incentives.

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