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Cross-regional emission reduction based on government-enterprise-public collaboration in the construction industry

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Abstract
Excessive carbon emissions are recognized as a significant contributor to climate change and environmental degradation. Achieving carbon neutrality has become an imperative for sustainable development. This study examined carbon emission reduction mechanisms in the construction industry, focusing on collaborative efforts among key stakeholders to achieve balance, coordination, and sustainability in carbon emission control. Employing Stackelberg game theory, the study analyzed the strategic interactions among the government, enterprises, and the public in collaborative efforts to reduce carbon emissions. It explored their mutual influences from a macro-scale perspective, examining the strategic choices made by each stakeholder and the specific impacts of various parameters on the key decisions. The study employed MATLAB software to simulate the effects of six key driving policies on system evolution. This research aimed to provide a robust theoretical foundation and practical guidance for establishing cross-sector collaborative mechanisms to reduce carbon emissions from the construction industry.

Introduction

In recent years, the continuous increase in carbon dioxide (CO_2) in the atmosphere has led to climate change, resulting in global warming, glacier and icecap melting, ocean acidification, and extreme weather events (An and Zhu, 2022; Barreca et al. 2016). These changes have threatened the environment and sustainable development. In response to this pressing challenge, the Intergovernmental Panel on Climate Change (IPCC) has repeatedly emphasized that reducing carbon emissions is crucial for mitigating the impacts of climate change (Eggleston et al. 2006). Since 1990, the international community has engaged in continuous negotiations on climate change, gradually reaching a consensus among nations. Collectively, the UNFCCC, Kyoto Protocol, Copenhagen Accord, and Paris Agreement convert climate consensus into economy-wide mitigation commitments that, for the construction sector, necessitate coordinated, cross-jurisdictional lifecycle emission reductions to internalize spatial spillovers (Bodansky, 1993; United Nations, 1997; Rogelj et al. 2010; Zhou, 2015).

These agreements have established essential institutions and frameworks to address climate change and have played a pivotal role in mitigating global warming. Different economic sectors contribute differently to carbon emissions. The *Research Report on Energy Consumption and Carbon Emission of Buildings in China* (2023) studied the total carbon emissions of China's construction sector in 2021. They reached a staggering 4.07 billion tons of CO_2,

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accounting for 38.2% of the national energy-related carbon emissions (China Building Energy Efficiency Association, 2024). Huang et al. (2018) analyzed the carbon emissions and energy intensity of the construction sector in 40 countries worldwide. They found that China's construction sector is the largest contributor to global growth in carbon emissions.

As a pillar of China's economy and one of the three major energy-consuming industries, the construction sector is characterized by high energy consumption, low energy efficiency, and significant pollution generation, necessitating urgent attention to its carbon emissions (Chen et al. 2017; Lynn et al. 2017). As the construction industry lies at the core of the economy, reducing its carbon emissions requires concerted efforts from various quarters of the community. Controlling carbon emissions and improving the energy efficiency of the construction industry can help mitigate the impacts of climate change. Establishing a mechanism to coordinate emissions reductions is paramount to transitioning to a low-carbon construction industry. The improvement is crucial to China's realization of the "dual-carbon" goals (Du et al. 2019).

Chinese cities are expected to reach a carbon emission peak by 2030 (Cheng et al. 2022) and carbon neutrality by 2060 (Li et al. 2022; Sun and Li, 2021). To achieve these national goals, collaborative governance is increasingly recognized as an effective strategy for driving carbon reduction efforts (Wang et al. 2020). Currently, China's carbon reduction initiatives primarily rely on an independent governance model based on administrative divisions and led by local governments (X. Liu et al. 2022). This model encompasses a range of measures, including setting region-specific emission reduction targets, promoting economic structural transformation, enhancing technological innovation, and launching carbon trading pilots at the provincial level (Pham et al. 2020; Zhao et al. 2021). However, due to the significant spatial spillover effects and regional mobility of carbon emissions, relying solely on this independent local governance model has proven inefficient and costly in practice (Xue et al. 2019).

As a result, improving existing governance methods and exploring more effective solutions has become an urgent priority (Liu et al. 2022). This study emphasizes that effective carbon reduction in the construction sector depends on the active participation and collaboration of three key stakeholders: the government, enterprises, and the public (hereinafter referred to as the "tripartite"). The persistent carbon-intensive behaviors of these stakeholders significantly contribute to urban carbon emissions (Cheng et al. 2021; Liu et al. 2020; Wang et al. 2020). Therefore, addressing entrenched high-carbon practices in construction, economic development, and consumption requires tripartite cooperation that balances interests and fosters low-carbon norms to achieve cross-regional emission reduction.

The Guangdong-Fujian-Zhejiang urban belt is a representative region of China's southeastern coastal urbanization, situated at the intersection of the Yangtze River Delta, the Pearl River Delta, the Taiwan region, and the Chinese mainland. Due to its strategic geographic position, open economy, and outward-oriented development strategy, it serves as a key bridge connecting the north-south and east-west economic corridors and as a frontier platform for cross-strait cooperation. These features make the Guangdong-Fujian-Zhejiang urban axis (hereinafter referred to as "the urban agglomeration") an ideal setting for examining the tripartite collaboration mechanism and developing cross-jurisdictional low-carbon governance models in the construction industry.

Building on this perspective, the present study makes three main contributions. First, it reframes emission reduction in the construction industry as a tripartite coordination problem that extends beyond administrative boundaries rather than a set of isolated local targets. Second, it constructs an evolutionary game model to analyze the dynamic strategic interactions among the government, enterprises, and the public, and to identify conditions for stable cooperation. Third, it applies this framework to the Guangdong-Fujian-Zhejiang coastal urban agglomeration, a region characterized by dense intercity linkages, strong construction demand, and active policy innovation, to propose a regional strategy for collaborative emission reduction and provide practical references for carbon peaking and neutrality policies.

Literature review

Research on collaborative carbon emission reduction in the construction industry

Regional synergy entails the collaboration of industries and enterprises across administrative units. In this process, local administrations must promote improvements in regional environmental quality through targeted investment, effective legislation, and robust enforcement. They can also foster synergy between environmental governance actions and public participation to achieve sustainable environmental improvement (Wu et al. 2020). Hu and Zhou (2021) emphasized the significance of collaborative environmental governance involving local governments, enterprises and the public in addressing pollution spillovers and cultivating a sense of regional ecological integration. Chong and Sun (2020) demonstrated that environmental regulation, as a systematic process that combines strategic interaction and policy effects, is pivotal to improving environmental quality. Similarly, Yang et al. (2018) emphasized the importance of government oversight, enterprise technology adoption, and public participation in collective emission-reduction actions.

In addition, Zhao and Chen (2018) found that enterprise behavior, local economic conditions, and public participation have a substantial influence on the governance strategies of local governments and firms. Wang and Wang (2018) demonstrated that effective environmental regulation promotes corporate emission reduction, although its effectiveness depends on the company's financial capacity. Liu et al. (2022) proposed a multi-stakeholder governance framework encompassing the "government–enterprise–consumer" tripartite and empirically verified its effectiveness. These studies collectively underscore the importance of multi-actor collaboration for emission-reduction governance, providing both theoretical foundations and policy guidance for sustainable environmental improvement.

At the regional level, synergy relies on industrial clustering and interconnected value chains to promote differentiated yet coordinated development. Empirical analyses of the Yangtze River Delta and Beijing–Tianjin–Hebei regions (He et al. 2016; Li et al. 2018; Shi et al. 2018) confirm that regional integration and market coordination can reduce pollution intensity and enhance carbon-emission efficiency through technology diffusion, institutional upgrading, and structural optimization. However, industrial agglomeration can also lead to emission concentration if not accompanied by effective regulation. Li and Wang (2014) demonstrated that the mitigation effect of clustering depends on governance intensity, innovation, and the development of a circular economy. Subsequent studies revealed that technological innovation and regional heterogeneity determine whether clustering yields positive or negative environmental outcomes (Zhu and Xia, 2018; Zhao et al. 2020). Furthermore, research on carbon leakage and industrial relocation has revealed complex spatial dynamics. Using input-output models, Lin and Sun (2010) and Gros et al. (2010) found that unilateral emission-reduction policies can trigger carbon leakage, while Xiao et al. (2014) and M. Li et al. (2022) observed that industrial transfers from eastern to western China often shift emissions rather than reduce them overall. Recent lifecycle and embodied-carbon analyses (S. Wang et al. 2022; Yang et al. 2024) highlight that heavy-industry-dominated supply chains remain the core of regional carbon collaboration networks.

In summary, existing studies have deepened the understanding of how multi-stakeholder cooperation, environmental regulation, and regional integration contribute to emission reduction. They provide strong theoretical and empirical foundations for collaborative environmental governance. However, most research remains fragmented, focusing either on single-actor behaviors or on specific industrial clusters, and often neglecting the dynamic interactions among the government, enterprises, and the public within a unified analytical framework. Therefore, a more systematic approach is needed to integrate multi-stakeholder decision-making and cross-regional coordination into one coherent model. Addressing this gap, the present study constructs an evolutionary game framework to simulate the behavioral dynamics of the tripartite actors in the construction industry, offering a new analytical perspective on collaborative and cross-jurisdictional emission reduction.

Research on the game model method

Low-carbon policies have prompted extensive use of game theory to analyze emission-reduction decision-making. Most studies focus on the strategic interaction between governments and enterprises. For instance, Wu et al. (2017) examined how government incentives facilitate the diffusion of low-carbon strategies among firms. Moledina et al. (2003) investigated corporate environmental behavior under different regulatory regimes. Sheu and Chen (2012) suggested that green tax and subsidy policies can effectively stimulate low-carbon supply chains. Similarly, Wang et al. (2022) and Liu et al. (2021) developed carbon-quota-based models for energy enterprises. Haghighi et al. (2021) applied a game-theoretic approach to Iran's power-sector expansion planning, demonstrating that appropriately designed taxes and subsidies can significantly reduce carbon emissions.

More recently, research has expanded toward multi-agent frameworks. For example, Wang et al. (2022) established a three-party model for urban decarbonization, and Yu et al. (2022) constructed two- and three-party evolutionary games to reveal the joint influence of enterprises and governments on carbon trading behavior. Collectively, these studies highlight that strategic interaction and policy design are critical determinants of emission-reduction outcomes.

However, most existing models remain confined to two-party analyses and fail to capture the complex evolutionary dynamics among multiple stakeholders. The construction industry, characterized by high energy intensity and strong interconnections among actors, has received limited scholarly attention. Furthermore, research examining public participation often adopts a purely regulatory perspective, overlooking behavioral inertia, financial constraints, and social motivation. Therefore, there is an urgent need for a dynamic, multi-stakeholder framework tailored to the construction sector that can better reflect tripartite coordination and cross-regional collaboration.

From a broader perspective, achieving low-carbon development within an urban agglomeration requires a systematic governance approach that balances carbon neutrality objectives with economic development goals. Sole reliance on government-led policies is insufficient to ensure sustainable outcomes. Enterprises and the public must also be actively engaged despite existing financial and behavioral barriers. Effective emission reduction thus depends on aligning the interests and responsibilities of the tripartite stakeholders across regions.

In summary, although previous studies have provided valuable insights into low-carbon governance and the application of game theory, they remain fragmented and largely sector-specific. Few studies have integrated multi-stakeholder dynamics with cross-regional collaboration, particularly within the construction industry, where emission sources, policy responsibilities, and behavioral interactions are deeply intertwined. This knowledge gap constrains understanding of how government, enterprise, and public behaviors coevolve under spatial spillovers and policy linkages.

To address these deficiencies, the present study develops a tripartite evolutionary game model that simultaneously captures the strategic behaviors and dynamic interactions among governments, enterprises, and the public within a cross-regional governance framework. By integrating behavioral evolution, coordination incentives, and spatial interdependence, the model enhances theoretical understanding of collaborative emission reduction and provides a systematic analytical basis for designing cross-regional collaborative emission-reduction strategies in the construction sector. This framework also lays the foundation for the subsequent model construction and simulation analysis.

Establishing the evolutionary game model

Basic assumptions of the model

The following assumptions are made to construct a game model for the construction industry in the urban agglomeration and to study the multi-regional carbon emission reduction mechanism in the multi-center construction industry.

Hypothesis 1 (H1). The construction enterprise is Participant 1, the public is Participant 2, and the local government is Participant 3. All three parties aim to maximize their interests and make rational choices about emission-reduction strategies over time, which tends to be optimal.

Hypothesis 2 (H2). The strategy space of construction enterprises is α $(\alpha_1, \alpha_2) =$ (active participation in cross-regional emission reduction, negative participation in cross-regional emission reduction). Assume that the probability of choosing α_1 is x and the probability of choosing α_2 is $1 - x$, $x \in [0, 1]$.

Table 1 Tripartite game payment matrix concerning participation in cross-regional collaborative emission reduction.

Enterprise	Public	Government: Active participation z	Government: Negative participation $1-z$
Active participation x	Active participation y	$R_T - C_{kh} + M_q$ $X_t - C_{ph} + M_p$ $A_g - C_g - M_q - M_p$	$R_T - C_{kh}$ $X_t - C_{ph}$ $A_g - T_g$
	Negative participation $1-y$	$R_T - C_{kh} + M_q$ $X_t - C_{pl}$ $A_g - C_g - M_q$	$R_T - C_{kh}$ $X_t - C_{pl}$ $A_g - T_g$
Negative participation $1-x$	Active participation y	$R_T - C_{kl} - F_p - B_q$ $X_t - C_{ph} + M_p$ $-C_g - M_p + F_p + B_q$	$R_T - C_{kl}$ $X_t - C_{ph}$ $-C_g - T_g$
	Negative participation $1-y$	$R_T - C_{kl} - F_p - B_q$ $X_t - C_{ph} + S_T$ $-C_g + F_p + B_q$	$R_T - C_{kl}$ $X_t - C_{pl} - S_T$ $-C_g - T_g$

Similarly, the strategy space of the public is β $(\beta_1, \beta_2) =$ (active participation in cross-regional emission reduction, negative participation in cross-regional emission reduction). Assume that the probability of choosing β_1 is y and the probability of choosing β_2 is $1-y$, $y \in [0, 1]$. The strategy space of local governments is r $(r_1, r_2) =$ (active participation in cross-regional emission reduction, negative participation in cross-regional emission reduction). Assume that the probability of choosing r_1 is z and the probability of choosing r_2 is $1-z$, $z \in [0,1]$.

Hypothesis 3 (H3). The benefits generated by construction enterprises' construction activities are as follows R_T. The cost of construction enterprises actively participating in emission reduction is C_{kh}, while the cost of their negative participation in emission reduction is C_{kl}, which satisfies the requirement $C_{kh} > C_{kl}$. Active participation in cross-regional emission reduction will bring local governments a comprehensive benefit A_g, which includes fiscal revenues from central subsidies, increased regional investment attractiveness, environmental benefits arising from reduced carbon intensity and mitigated pollution, and social and political gains reflected in higher public satisfaction and improved governance performance. Enterprises that participate passively in cross-regional emission reduction will be required to pay eco-compensation B_q to the government to offset the environmental losses caused by their excessive emissions.

Hypothesis 4 (H4). The benefits of construction enterprises' activities to the public's production and life are X_t. If construction enterprises are negatively involved in cross-regional emission reduction, and the public is not involved in supervision. Thus, the loss of environmental impacts caused by carbon emissions to the public is S_Y. When the public actively participates in cross-regional emission reduction, the cost is C_{ph}, and when the public negatively participates in cross-regional emission reduction, the cost is C_{pl}. Active participation in cross-regional emission reduction requires more time and resources, which satisfies the requirement $C_{ph} > C_{pl}$. The government can reward public participation in emission-reduction activities as M_p.

Hypothesis 5 (H5). Local governments actively participating in cross-regional emission reduction activities can obtain subsidies from the central government as M_q, while penalties for non-participation in emission reduction are denoted as F_q. The administrative cost for local governments to actively participate in cross-regional emission reduction is C_g, and the environmental loss caused by the imbalance of carbon emissions in the construction industry due to negative participation in cross-regional emission reduction is T_g, which satisfies the requirement of $T_g > C_g$.

Constructing the model

Establishing a tripartite game payment matrix for cross-regional collaborative emission reduction in the construction industry in the urban agglomeration, as shown in Table 1.

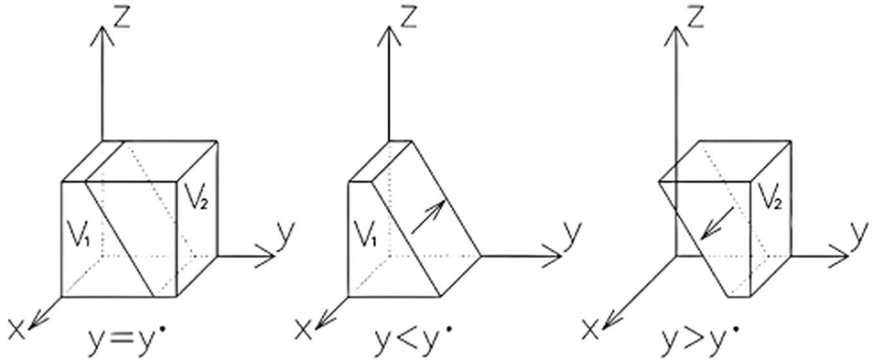

Fig. 1 Evolutionary phase of strategies for construction enterprises. The phase trajectory illustrates the dynamic evolution of enterprise strategies under baseline parameter settings.

Multi-subject game equilibrium analysis

Stability analysis of construction enterprise strategies

The participation stances of construction industry enterprises in cross-regional collaborative emission reduction activities are significantly influenced by the anticipated benefits and their average values. They may actively engage or adopt a more negative, conservative, wait-and-see approach. The expected returns and average expected returns (E_{11}, E_{12}, $\overline{E}_1$) of construction industry enterprises opting to participate in cross-regional collaborative emission reduction actively or to refrain from such participation are:

$$E_{11} = yz(R_T - C_{kh} + M_q) + y(1-z)(R_T - C_{kh}) + (1-y)z(R_T - C_{kh} + M_q) + (1-y)(1-z)(R_T - C_{ih}) \quad (1)$$

$$E_{12} = yz(R_T - C_{kl} - F_p - B_q) + y(1-z)(R_T - C_{kl}) + (1-y)z(R_T - C_{kl} - B_q) + (1-y)(1-z)(R_T - C_{kl}) \quad (2)$$

$$\overline{E}_1 = xE_{11} + (1-x)E_{12} \quad (3)$$

The replicated dynamic equation for strategy selection in construction enterprises can be expressed as:

$$F(x) = \frac{dx}{dt} = x(E_{11} - \overline{E}_1) = x(1-x)[(yz-y)(M_q + B_q) + C_{kl} - C_{kh} + M_q + B_q] \quad (4)$$

The first-order derivatives and the set $G(y)$ are:

$$\frac{dF(x)}{dx} = (2x-1)[(yz-y)(M_q + B_q) + C_{kl} - C_{kh} + M_q + B_q \quad (5)$$

$$G(y) = (yz-y)(M_q + B_q) + C_{kl} - C_{kh} + M_q + B_q \quad (6)$$

According to the stability theorem for the differential equation, the probability of a construction enterprise choosing to participate in cross-regional collaborative emission reduction must reach and remain at a stable state: and $\frac{dF(x)}{dx} < 0$. Because $\partial G(y)/\partial y = (z-1)(M_q + B_q)$, $0 < z < 1$, $M_q, B_q > 0$, so when $\partial G(y)/\partial y < 0$, $G(y)$ is a decreasing function on y. Therefore, when $y = \frac{C_{kl} - C_{kh} + M_q + B_q}{(1-z)(M_q + B_q)} = y^*$, $G(y) = 0$, at this time, $\frac{dF(x)}{dx} \equiv 0$, the construction enterprises can not determine the stabilization strategy, when $y < y^*$, at this time, $\frac{dF(x)}{dx}|_{x=0} < 0$ for the evolutionary stabilization strategy (ESS) of the construction enterprises, on the contrary, when $y > y^*$, $x = 1$ for the ESS. The evolution of strategy in construction enterprises is shown in Fig. 1.

Figure 1 shows that the volume of V_1 is the probability that a construction enterprise is negatively involved in cross-regional collaborative emission reduction, and the volume of V_2 is the probability that a construction enterprise is actively involved in cross-regional collaborative emission reduction, then:

$$V_1 = \int_0^1 \int_0^1 \frac{C_{kl} - C_{kh} + M_q + B_q}{(1-z)(M_q + B_q)} dzdx \tag{7}$$

$$V_2 = 1 - V_1 = 1 + \left(\frac{C_{kl} - C_{kh}}{M_q + B_q} + 1 \right) \ln(1 - z) \tag{8}$$

Corollary 1 (C1): The propensity of enterprises to participate in collaborative emission reduction is proportional to the incentives provided by local governments (M_q), and is also positively associated with the ecological compensation mechanism (B_q). In addition, the cost saved by enterprises through negative participation in collaborative emission reduction, that is, the difference between choosing a lower-cost emission reduction plan and a higher-cost emission reduction plan ($C_{kl} - C_{kh}$), also positively affects their probability of participation.

Proof: According to the expression for V_2, by solving the first-order partial derivatives of each element, we find that: $\partial V_2/\partial M_q > 0$, $\partial V_2/\partial B_q > 0$, $\partial V_2/\partial(C_{kh} - C_{kl}) > 0$. Therefore, if M_q, B_q and $C_{kh} - C_{kl}$ increase, they all increase the probability that construction enterprises will actively participate in cross-regional collaborative emission reduction.

C1 indicates that local governments have multiple tools to motivate construction enterprises to actively participate in cross-regional collaborative emission reduction, not only through incentives to enhance their willingness to participate but also by increasing the eco-compensation given to the government to regulate the behavior of the enterprises. In addition, the study found that construction enterprises are more sensitive to the cost difference between active and passive participation in cross-regional collaborative emission reduction. They are more likely to participate in cross-regional collaborative emission reduction activities when the cost difference is small.

Corollary 2 (C2): In the evolutionary process, the probability that construction enterprises actively participate in cross-regional collaborative emission reduction is positively correlated with the probability that the public and local governments participate in cross-regional collaborative emission reduction.

Proof: Through an analysis of the stability of construction enterprises' strategies, it becomes evident that when $z < \frac{C_{kh} - C_{kl}}{M_q + B_q} - 1$, $y < y^*$, at this time, $G(y) > 0$, $\frac{dF(x)}{dx}|_{x=0} < 0$, the ESS corresponds to $x = 0$, and conversely, $x = 1$ for ESS. Consequently, as the variables y and z increase, the stable strategy of construction enterprises transitions from $x = 0$ (active participation in cross-regional collaborative emission reduction) to $x = 1$ (negative participation in cross-regional collaborative emission reduction).

C2 indicates that as the probability of public participation in cross-regional collaborative emission reduction increases, this trend will significantly encourage construction companies to participate more actively in such actions. Local governments play a crucial role in this process. Not only can they lead construction enterprises to follow up by directly participating in cross-regional collaborative emission reduction activities, but they can also use publicity and education to raise the public's awareness of the responsibility of emission reduction, which indirectly promotes the participation of construction enterprises in the cross-regional collaborative emission reduction. In this way, the local government establishes a model for cooperative emissions reduction among construction enterprises. Additionally, it strongly supports enhancing public awareness of environmental protection and building a social atmosphere for green development. These multidimensional interactions and cooperation provide a solid social foundation and policy guarantees for achieving regional and even global carbon emissions control targets.

Stability analysis of public social strategies

When examining the general public's motivation to participate in cross-regional collaborative emission-reduction actions, their anticipated benefits and average expected returns are pivotal factors in decision-making. The expected returns and average expected returns (E_{21}, E_{22}, $\overline{E}_2$) of the public selecting to engage actively in cross-regional collaborative emission

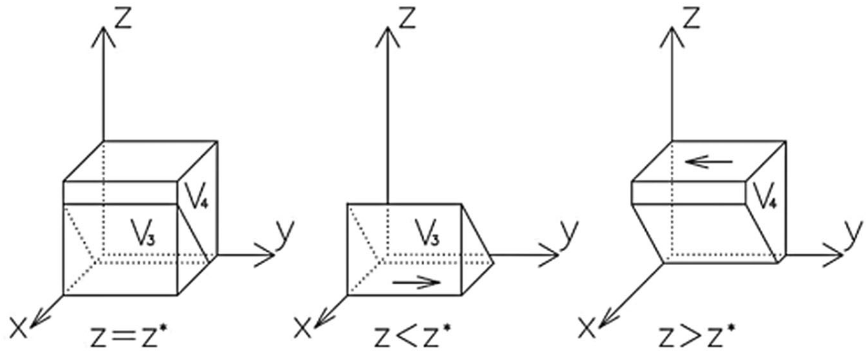

Fig. 2 Evolutionary phase of strategies for the public. The phase trajectory illustrates the dynamic evolution of public participation strategies under baseline parameter settings.

reduction or to abstain from such participation are:

$$E_{21} = xz(X_t - C_{ph} + M_p) + x(1-z)(X_t - C_{ph}) + (1-x)z(X_t - C_{ph} + M_p) + (1-x)(1-z)(X_t - C_{ph}) \tag{9}$$

$$E_{22} = xz(X_t - C_{pl}) + x(1-z)(X_t - C_{pl}) + (1-x)z(X_t - C_{pl} - S_T) + (1-x)(1-z)(X_t - C_{pl} - S_T) \tag{10}$$

$$\overline{E}_2 = xE_{21} + (1-x)E_{22} \tag{11}$$

The replicated dynamic equations, first-order derivatives, and $J(z)$ for the strategic choices of the social public are:

$$F(y) = dy/dt = y(E_{21} - \overline{E}_2) = y(y-1)[zM_p + (1-x)S_T + C_{pl} - C_{ph}] \tag{12}$$

$$\frac{d(F(y))}{dy} = (2y-1)[zM_p + (1-x)S_T + C_{PL} - C_{ph}] \tag{13}$$

$$J(z) = zM_p + (1-x)S_T + C_{pl} - C_{ph} \tag{14}$$

According to the stability theorem for differential equations, the probability of the public choosing cross-regional collaborative emission reduction must satisfy a stable state $d(F(y))/dy < 0$. Because $J(z)$ is an increasing function, when $z = \frac{C_{ph}-C_{pl}-(1-x)S_T}{M_P} = z^*$, $J(z) = 0$, at this time, $\frac{dF(y)}{dy} \equiv 0$, $F(y) \equiv 0$. The social public cannot determine the stabilization strategy, and when $z > z^*$, $J(z) > 0$, $\frac{dF(y)}{dy}\big|_{y=0} < 0$, $y = 0$ is the social public ESS, and on the contrary, when $z > z^*$ $y = 1$ is the ESS. The evolution of the social public strategy is shown in Fig. 2.

Figure 2 shows the tangent plane passing through the point $(1 - \frac{C_{ph}-C_{pl}}{S_r}, 0, 0)$. The volume of V_3 is the probability of public active participation in cross-regional collaborative efforts to reduce emissions. The volume of V_4 is the probability of negative public participation in cross-regional collaborative emission reduction. Therefore:

$$\begin{aligned} V_3 &= \int_0^1 \int_0^{1-\frac{C_{ph}-C_{pl}}{S_T}} \frac{C_{ph}-C_{pl}-(1-x)S_T}{M_p} d_x d_y \\ &= \frac{(C_{ph}-C_{pl}-S_T)^2}{M_P S_T} + \frac{C_{ph}-C_{pl}-S_T}{2S_T} \\ &= \frac{(2+M_P)(C_{ph}-C_{pl}-S_T)^2}{2M_P S_T} \end{aligned} \tag{15}$$

$$V_4 = 1 - V_3 = 1 - \frac{(2+M_P)(C_{ph}-C_{pl}-S_T)^2}{2M_P S_T} \tag{16}$$

Corollary 3 (C3): There is a negative correlation between the probability of the public choosing to actively participate in the cross-regional collaborative emission reduction and the cost saved by choosing to negatively participate in the cross-regional collaborative emission reduction, while there is a positive correlation between the incentives provided by the local government for the active participation of the social groups in the cross-regional collaborative emission reduction and the loss of the public's life and production due to the carbon emissions generated by the construction industry.

Proof: According to the expression of the probability of the public choosing to actively participate in cross-regional collaborative emission reduction, solving the first-order partial derivatives of each element, it can be obtained that: $\partial V_3/\partial M_p > 0$, $\partial V_3/\partial S_T > 0$, $\partial V_3/\partial(C_{ph} - C_{pl}) < 0$. Therefore, when M_p, S_T or $C_{ph} - C_{pl}$ is lowered, it can increase the probability of public active participation in cross-regional collaborative emission reduction.

C3 suggests that the government can encourage participation by increasing incentives for the public to engage in cross-regional collaborative emission-reduction behaviors and activities. At the same time, as carbon emissions from construction activities in the building industry increase, so do the losses to the public's daily behaviors and activities. Consequently, the likelihood that the public will actively participate in cross-regional collaborative emission-reduction activities increases. At the same time, public participation in cross-regional collaborative emission reduction is also influenced by differences in behavioral costs between active and passive participation. The smaller the difference in behavioral costs, the higher the probability of public participation in cross-regional collaborative emission reduction activities.

Corollary 4 (C4): The probability of local governments or construction actively participating in cross-regional collaborative carbon emission reduction increases, and the probability of the public participating actively in cross-regional collaborative emission reduction gradually decreases during evolution.

Proof: The analysis of the stability of the public strategy shows that $y = 1$ is ESS when $z > z^*$, $x > \frac{C_{ph} - C_{pl} - (1-x)S_T}{M_P} = x^*$, and vice versa, $y = 0$ is ESS when $z < z^*$ $x < x^*$. Therefore, with the increase in and the stable strategy of public participation in collaborative carbon emission reduction, the construction industry's strategy of public participation shifts from $y = 1$ (active participation in cross-regional collaborative emission reduction) to $y = 0$ (negative participation in cross-regional collaborative emission reduction).

C4 suggests that the interaction and choice of strategic decision-making between construction enterprises and local governments will influence the stabilization strategy of the public. When local governments and construction enterprises participate in cross-regional collaborative emission reduction, the public tends to view the initiative negatively as a stabilizing choice. The active participation of local governments and construction enterprises as the main participants in cross-regional collaborative emission reduction will weaken public awareness of emission reduction. Therefore, when local governments and construction enterprises actively participate in the cross-regional collaborative emission reduction strategy, local governments have an important mission: to strengthen publicity, education and mobilization to guide the public to join the cross-regional collaborative emission reduction action.

Stability analysis of local government strategies

The participation stance of local governments in cross-regional collaborative emission reduction initiatives, whether they actively participate or adopt a more conservative, wait-and-see approach, is notably influenced by the expected benefits and their average values. The expected returns and average expected returns (E_{31}, E_{32}, $\overline{E}_3$) of local governments opting to engage actively in cross-regional collaborative emission reduction or to abstain from such involvement are as follows:

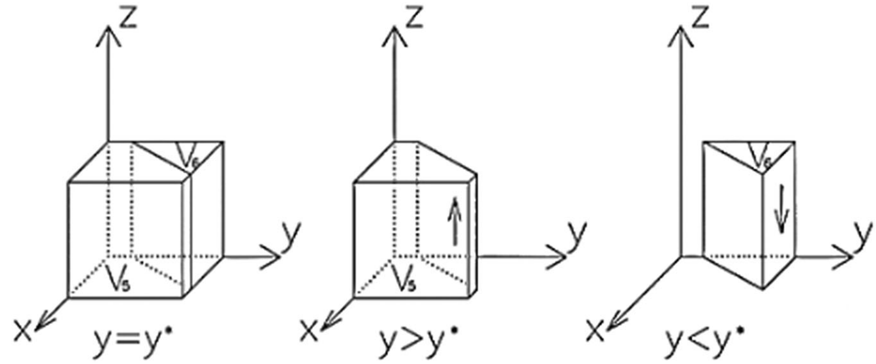

Fig. 3 Evolutionary phase of strategies for the local government. The phase trajectory illustrates the dynamic evolution of government strategies under baseline parameter settings.

The replication dynamic equation for local governments choosing to participate in cross-regional collaborative emission reduction is:

$$E_{31} = xy(A_g - C_g - M_q - M_p) + x(1-y)(A_g - C_g - M_q) + (1-x)y(-C_g - M_p + F_p + B_q) \tag{17}$$

$$E_{32} = xy(A_g - T_g) + x(1-y)(A_g - T_g) + (1-x)y(-C_g - T_g) + (1-x)(1-y)(-C_g - T_g) \tag{18}$$

$$\overline{E}_3 = xE_{31} + (1-x)E_{32} \tag{19}$$

The first-order derivatives as well as $H(y)$ are:

$$F(z) = dz/dt = z(1-z)[x(-C_g - F_p - B_q) - yM_p + F_p + B_q + T_g] \tag{20}$$

$$\frac{dF(z)}{dz} = (2z-1)[x(-C_g - F_p - B_q) - yM_p + F_p + B_q + T_g] \tag{21}$$

$$H(y) = x(-C_g - F_p - B_q) - yM_p + F_p + B_q + T_g \tag{22}$$

The local governments choosing the cross-regional collaborative emission reduction strategy in the stable state must satisfy:$F(z) = 0$, $\frac{dF(z)}{dz} < 0$, since $\partial H(y)/\partial y < 0$, so $H(y)$ is a decreasing function y. So when $y = \frac{x(-C_g - F_p - B_q) + F_p + B_q + T_g}{M_n} = y^*$, $H(y) = 0$, $\frac{dF(z)}{dz} \equiv 0$, the stable strategy cannot be determined. When $y > y^*$, $H(y) < 0$, $\frac{\mathrm{d}F(z)}{\mathrm{d}z}\big|_{z=1} < 0$, then $z = 1$ is ESS and vice versa $z = 0$ is ESS. The evolution phase of local governments' strategy is shown in Fig. 3.

The volume of V_5 is the probability that the local governments actively participate in cross-regional collaborative emission reduction. The volume of V_6 is the probability that the local government will negatively participate in cross-regional collaborative emission reduction. Therefore:

$$V_5 = \int_0^1 \int_0^1 \frac{x(-C_g - F_p - B_q) + F_p + B_q + T_g}{M_p} dxdy = \frac{F_p + B_q - C_g + 2T_g}{2M_p} \tag{23}$$

$$V_6 = 1 - \frac{F_p + B_q - C_g + 2T_g}{2M_p} \tag{24}$$

Corollary 5 (C5): There is a significant correlation between the propensity of local governments to participate in cross-regional collaborative carbon emission reduction activities and the incentives and constraints they face. Specifically, the likelihood of local governments' active participation in collaborative regional emission reduction is

Table 2 Equilibrium point stability analysis.

Equilibrium point	Eigenvalues of the Jacobi matrix $\lambda_1, \lambda_2, \lambda_3$	Real symbol	Stability analysis	Condition
E_1	$C_{kh} - C_{kl} - M_q - B_q$, $C_{ph} - C_{pl} - S_T$, $-F_p - B_q - T_g$	(−, −, −)	ESS	①
E_2	$C_{kl} - C_{kh} + M_q + B_q$, $C_{ph} - C_{pl}$, $C_g - T_g$	(×, +, ×)	Unstable point	
E_3	$C_{kh} - C_{kl} + M_q + B_q$, $C_{pl} - C_{ph}$, $M_p - F_p - B_q - T_g$	(+, −, ×)	Unstable point	
E_4	$C_{kh} - C_{kl} - M_q - B_q$, $C_{ph} - C_{pl} - M_p - S_T$, $F_p + B_q + T_g$	(×, ×, +)	Unstable point	
E_5	$C_{kl} - C_{kh} + M_q + B_q$, $C_{ph} - C_{pl} - M_p$, $C_g + M_p - T_g$	(−, −, −)	ESS	②
E_6	$C_{kl} - C_{kh} + M_q + B_q$, $C_{ph} - C_{pl} - M_p$, $-C_g - F_p - B_q$	(×, ×, −)	Unstable point	
E_7	$C_{kh} - C_{kl} - M_q - B_q$, $M_p + S_T + C_{pl} - C_{ph}$, $-M_p + F_p + B_q + T_g$	(×, 0, ×)	Unstable point	
E_8	$C_{kl} - C_{kh} + M_q + B_q$, $M_p + C_{pl} - C_{ph}$, $-C_g - M_p + T_g$	(×, ×, ×)	Unstable point	
E_9	$[\frac{F_p+B_q+T_g}{M_p}(\frac{C_{ph}-C_{pl}-S_T}{M_p} - 1)(M_q + B_q)$ $- \frac{2(F_p+B_q+T_g)}{M_p}, C_{kl} - C_{kh} + M_q + B_q]$, $-(1 - \frac{C_{ph}-C_{pl}-S_T}{M_p})(C_{ph} - C_{pl} - S_T)$	(×, −, −)	Unstable point	
E_{10}	$\frac{(T_g-C_g)(C_{ph}-C_{pl}-M_p)(M_p+B_q)}{M_p^2}$ $\frac{2(T_g-C_g)-M_p}{M_p}, C_{kl} - C_{kh} + M_q + B_q$, $\frac{2(C_{ph}-C_{pl})-M_p}{M_p}(T_g - C_g - M_p)$,	(×, ×, ×)	Unstable point	
E_{11}	$\frac{F_p+B_q+(T_g-M_p)-C_g}{2(C_g+F_p+B_q)}, \lambda_2, \lambda_3$ $\lambda_2 = \lambda_3 = zM_p + (1 - \frac{F_p+B_q+T_g-M_p}{C_g+F_p+B_g})S_T)/2$ $-(F_p + B_q + T_g - M_p)/2(C_g + F_P + B_q) + \cdots$	(+, 0, 0)	Inconclusive	

× indicates that the real symbol could not be determined, and the serial number indicates that the equilibrium point makes sense under that condition.

Condition ①: $C_{kh} - C_{kl} - M_q < B_q$, $C_{ph} - C_{pl} > S_T$.

②: $C_{kh} - C_{kl} - M_q > B_q$, $C_{ph} - C_{pl} > M_p$, $C_g + M_p < T_g$.

positively correlated with the penalty levels imposed on construction enterprises for negative participation, the compensation costs paid by enterprises for eco-environmental protection, and the penalties imposed by the central government on negative local government behavior. On the contrary, the probability of local government participation is negatively correlated with the regulatory costs borne by local governments and the incentives they provide to encourage public participation in cross-regional collaborative emission reduction.

Proof: Taking the first-order partial derivatives of each element according to equation V_5, we get: $\partial V_5/\partial F_p > 0$, $\partial V_5/\partial B_q > 0$, $\partial V_5/\partial F_p > 0$, $\partial V_5/\partial B_q > 0$, $\partial V_5/\partial T_g > 0$, $\partial V_5/\partial C_g > 0$, $\partial V_5/\partial M_P < 0$. Therefore, an increase in F_p, B_q, T_g or a decrease in C_g, M_p can increase the likelihood that local governments actively participate in cross-regional collaborative emission reduction.

C5 indicates that the economic penalties imposed by the local government on the negative participation of construction enterprises in cross-regional collaborative emission reduction activities, as well as the eco-compensation fees paid by the enterprises to compensate for the environmental impacts, have been proven to be effective in increasing the probability of active participation of the local government in such collaborative emission reduction activities. At the same time, the increase in penalties imposed by central governments on local governments' negative behaviors in cross-regional collaborative emission-reduction activities further strengthens local governments' sense of urgency to fulfill their emission-reduction responsibilities. However, the economic costs that local governments must bear when actively participating in cross-regional collaborative emission reduction, and the incentives they offer to encourage participation from all community sectors, are inversely related to local governments' motivation to participate.

Corollary 6 (C6): In the evolution process, the tendency of local governments to participate in cross-regional collaborative emission reduction shows a positive correlation. As the willingness of construction enterprises and the public to participate in cross-regional collaborative emission reduction increases, so does the likelihood that local governments will participate.

Proof: From the analysis of the evolutionary stability of the local government's strategy choice, $z = 1$ is ESS when $y > y^*$, at this time, $x > \frac{yM_p - F_p + B_q + T_g}{C_g + F_p + B_q}$.

As y and x increase, the probability that a local government is actively involved in cross-regional collaborative emission reduction decreases from $z = 1$ to $z = 0$. Thus, there exists a decrease in z as x and y increase.

C6 indicates that the enthusiasm and determination of local governments to engage in cross-regional collaborative emission reduction are often significantly influenced by the strategic choices made by construction companies and the public. When construction companies or the general public exhibit a higher degree of active participation, local governments' willingness to participate may be challenged, and they may even adopt a posture of passive participation.

Stability analysis of the equilibrium point of the tripartite evolutionary game

The equilibrium point of the system is obtained from $F(x) = 0$, $F(y) = 0$, $F(z) = 0$: E_1 (0, 0, 0), E_2 (0, 0, 0), E_3 (0, 0, 0), E_4 (0, 0, 0), E_5 (0, 0, 0), E_6 (0, 0, 0), E_7 (0, 0, 0), E_8 (1, 1, 1), E_9 (0, $\frac{F_p+B_q+T_g}{M_p}$, $\frac{C_{ph}-C_{pl}-S_T}{M_p}$), E_{10} (0, $\frac{T_g-C_g}{M_p}$, $\frac{C_{ph}-C_{pl}}{M_p}$), E_{11} ($\frac{F_p+B_q+T_g-M_p}{C_g+F_p+B_q}$, 1, $\frac{C_{kh}-C_{kl}}{M_q+B_q}$), where x, y, $z \in [0, 1]$, E_9 ~ E_{11} make sense under certain conditions.

The Jacobian matrix of the tripartite evolutionary game system is expressed as:

$$J = \begin{pmatrix} (2x-1)[(yz-y)(M_q+B_q)+C_{kl}-C_{kl}+M_q+B_q] & x(1-x)(z-1)(M_q+B_q) & xy(1-x)(M_q+B_q) \\ -y(1-y)S_T & (2y-1)[zM_p+(1-x)S_r+C_{pl}-C_{ph}] & y(1-y)M_p \\ z(1-z)[x(-C_g-F_p-B_q)] & -z(1-z)M_p & (2z-1)[x(-C_g-F_p-B_q)-yM_p+F_p+B_q+T_g] \end{pmatrix} \tag{25}$$

According to Lyapunov stability theory, the system's equilibrium point is analyzed for stability, as shown in Table 2.

Corollary 7 (C7): There exists an asymptotic stabilization point E_1 (0, 0, 0) for the replicated dynamic equation when $C_{kh} - C_{kl} - M_q < B_q$ and $C_{ph} - C_{pl} < S_T$.

Proof: From Table 2, when $C_{kh} - C_{kl} - M_q < B_q$ and $C_{ph} - C_{pl} < S_T$, at this time, $C_{kh} - C_{kl} - M_q - B_q < 0$, $C_{ph} - C_{pl} - S_T < 0$, E_1 is the asymptotic stabilization point of the system.

C7 indicates that if the net cost of active versus passive participation (after accounting for eco-compensation) for construction enterprises in emission reduction is less than the incentives provided by the government, or if the cost difference for the general public is less than the detrimental effects of carbon emissions on their lives and production, there tends to be a preference for passive participation in emission reduction strategies. This could impede the effective formation of a collaborative mechanism among government, businesses, and society in the construction sector. To foster this collaboration, it is critical to adjust incentive structures so that the cost benefits of active participation, minus ecological compensation, outweigh the value of government incentives. Similarly, the societal benefits of active participation should outweigh the negative impacts of carbon emissions. Strategic adjustments like

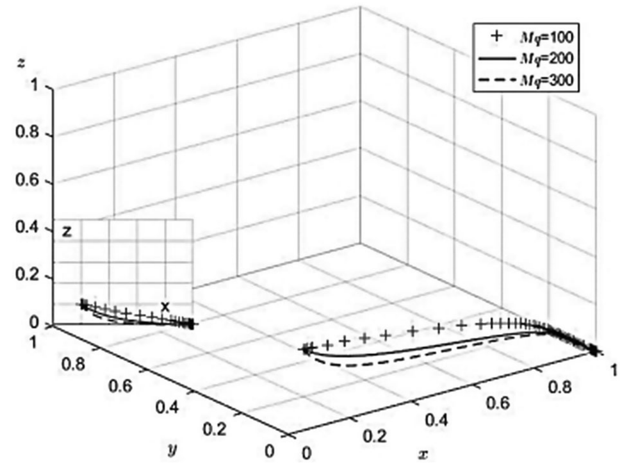

Fig. 4 The impact of enterprises' active participation incentives in cross-regional collaborative emission reduction. Simulation results show how varying incentive intensity affects enterprises' strategy evolution.

these can effectively encourage construction enterprises and the public to participate actively, thereby driving significant progress in environmental sustainability within the construction industry.

Corollary 8 (C8): There exists an asymptotic stabilization point E_5 (1, 1, 0) for the replicated dynamic equation when $C_{kh} - C_{kl} - M_q > B_q$, $C_{ph} - C_{pl} < M_p$ and $C_g + M_p < T_g$.

Proof: From Table 2, when $C_{kh} - C_{kl} - M_q > B_q$, $C_{ph} - C_{pl} < M_p$, $C_g + M_p < T_g$, at this time, $C_{kl} - C_{kh} + M_q + B_q < 0$, $C_{ph} - C_{pl} - M_p < 0$, $C_g + M_p - T_g < 0$, E_5 is the asymptotic stabilization point of the system.

C8 shows that when the cost difference between the ecological compensation set by the local government for construction enterprises and the reward for cross-regional collaborative emission reduction exceeds the ecological compensation, construction enterprises tend to participate actively in cross-regional collaborative emission reduction. If the public actively participates in cross-regional collaborative emission reduction, and the cost difference is smaller than the government incentive, their choices also tend to induce active participation in cross-regional collaborative emission reduction. In addition, when the cost borne by the local government for active participation in emission reduction, together with the total amount of its incentives to enterprises, is lower than the penalties imposed by the central government, the central government may adopt a passive stance in cross-regional collaborative emission reduction activities. However, this phenomenon suggests an important policy direction: increasing central government penalties can effectively incentivize local governments to participate more actively in cross-regional collaborative emission-reduction actions.

Numerical simulation analysis

We tested the validity of the evolutionary stability analysis using panel data on urban agglomerations. It was based on the construction industry's value added to the gross output and the cost of environmental protection in 16 cities in 2021. To simplify the calculations, we used the test's average gross output value-added for the construction industry (CNY57.433 billion) and the average environmental protection expenditure (CNY613.125 million) of the 16 cities as representative values. Numerical simulation analysis using MATLAB software, set array 1: $M_q = 250$, $B_q = 300$, $C_{kl} = 100$, $C_{kh} = 600$, $M_P = 100$, $S_T = 300$, $C_{Pl} = 80$, $C_{ph} = 160$, $C_g = 200$, $F_P = 150$, $T_g = 400$, to meet the condition ② in inference 8, based on array 1, analyze the impact of M_P, M_q, C_g, F_P, B_q, S_T changes in the game analysis and results. We analyze M_q. Assigning values of 100, 200, and 300 to M_q, and evolve the replicated dynamic system of equations 50 times. The results are shown in Fig. 4.

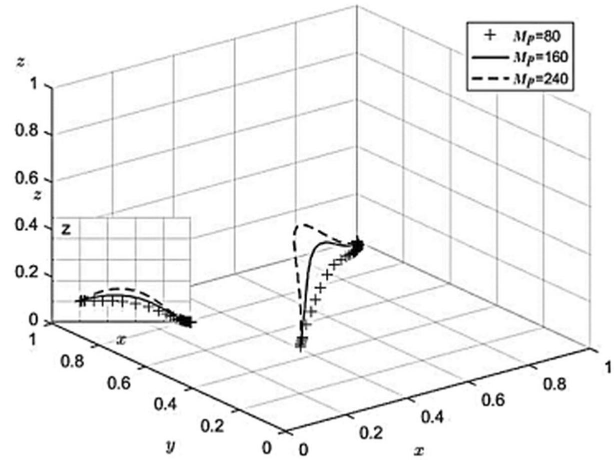

Fig. 5 The impact of the public's active participation incentives (R_2) in cross-regional collaborative emission reduction. Simulation results show how varying incentive intensity affects public participation dynamics.

Figure 4 shows that an increase in enterprise-oriented incentives M_q reshapes the interaction dynamics among the three participants in the game system. As M_q rises, construction enterprises gradually assume a dominant role in cross-regional collaborative emission-reduction activities, becoming the primary force driving system evolution. The simulation results display a steady upward trend in enterprise participation. In contrast, the participation of governments and the public declines slightly as the need for external administrative intervention diminishes once enterprises internalize the returns to emission reduction. This scenario highlights a firm-led coordination pathway, demonstrating that targeted enterprise incentives are the most direct and cost-effective approach to promoting large-scale collaboration and achieving stable cross-regional emission reduction outcomes.

Assigning values of 100, 200, and 300 to M_p, respectively, the replicated dynamic equation system evolves 50 times, with results displayed in Fig. 5. This demonstrates that increases in the public-oriented incentive M_p alter the coordination structure of cross-regional collaborative emission reduction by introducing a bottom-up transmission mechanism. As M_p rises, the probability of public participation increases markedly, thereby exerting a spillover effect on enterprises through social supervision and reputational pressure. Enterprises respond positively to this enhanced public engagement, while the government's participation remains relatively stable. This scenario reveals that public incentives influence collaboration primarily through social interaction channels rather than through direct fiscal leverage. Its unique contribution lies in identifying a civic-driven coordination pathway, in which active citizen participation indirectly promotes enterprise compliance and strengthens the overall stability of regional emission-reduction cooperation.

Assigning values of 100, 200, and 300 to C_g, respectively, the replicated dynamic equation system evolves 50 times, with results depicted in Fig. 6. This demonstrates that increases in the government's administrative cost parameter C_g exert a substantial constraining effect on the dynamics of cross-regional collaboration. As C_g rises, the probability of government participation declines, revealing a clear inverse correlation between the cost level and engagement intensity. The simulation indicates that higher administrative costs not only suppress the government's own involvement but also trigger a cascade effect, reducing the responsiveness of both enterprises and the public by weakening institutional coordination. This scenario identifies a cost-dominant regime in which excessive fiscal pressure can disrupt cross-regional collaborative mechanisms and destabilize cooperative equilibria. Its unique contribution lies in emphasizing that cost control and administrative efficiency are critical prerequisites for maintaining sustainable multi-agent cooperation in emission-reduction governance.

Assigning values of 150, 300, and 450 to F_P, respectively, the replicated dynamic equation system evolves 50 times, with results shown in Fig. 7. This illustrates that increasing the penalty coefficient F_P for enterprises' non-cooperative behavior produces a nonlinear adjustment effect on system dynamics. As F_P rises from a low to moderate level, the probability of enterprise participation increases as penalties effectively deter opportunistic or free-riding

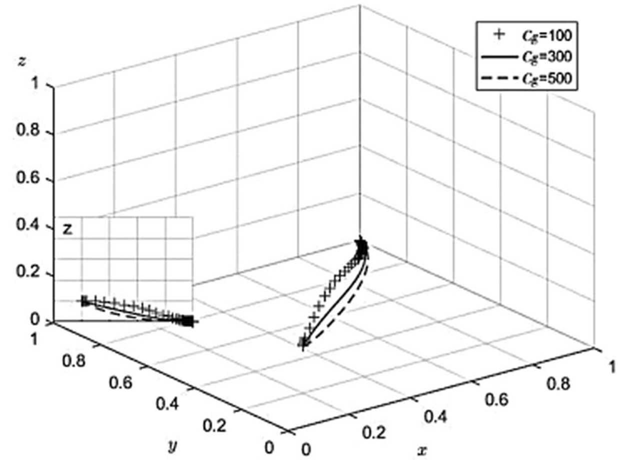

Fig. 6 The impact of local government's administrative costs (C_{g1}) in cross-regional collaborative carbon emission reduction. Simulation results show how cost changes influence the government's strategic evolution.

behavior. However, when F_P exceeds a certain threshold, the government's participation exhibits a reversal trend, first increasing and then declining due to the rising enforcement burden and administrative pressure. This scenario highlights a deterrence-fatigue trade-off, demonstrating that excessively severe penalties may reduce overall governance efficiency and weaken long-term coordination. Its unique contribution lies in defining an effective penalty band, within which fines can maintain compliance incentives without triggering administrative inefficiency.

Assigning values of 150, 300, and 450 to B_q, respectively, the replicated dynamic equation system evolves 50 times, with results displayed in Fig. 8. This reveals that increasing the ecological compensation parameter B_q introduces a fiscal feedback mechanism that reshapes the interdependence among the three actors. Moderate increases in B_q enhance local governments' willingness to participate by offsetting the fiscal burden of cross-regional collaboration, thereby reinforcing enterprises' and the public's cooperative behavior through stronger financial and institutional signals. However, when B_q exceeds a certain threshold, local government participation begins to decline due to the emergence of moral hazard and reduced marginal returns on compensation. This scenario highlights a pay-for-performance window in which ecological compensation effectively internalizes environmental spillovers only within a bounded range. Its unique contribution lies in identifying that well-calibrated compensation levels can sustain multi-party coordination, while excessive transfers may distort incentives and weaken long-term governance efficiency.

Assigning 300, 450, and 600 values to S_T and replicating the dynamic equation system 50 times generates Fig. 9. It shows that variations in the severity of environmental losses S_T trigger heterogeneous behavioral responses among the three participants. When S_T is low, construction enterprises tend to adopt a wait-and-see strategy, as the perceived environmental risks remain limited and economic considerations dominate. As S_T increases, both local governments and the public exhibit accelerated engagement, reflecting heightened environmental awareness and risk sensitivity. Once losses surpass a critical level, enterprises' strategic preferences shift toward cooperation to avoid potential regulatory penalties and reputational damage. This scenario identifies a risk-perception threshold within which actors transition from passive observation to proactive collaboration. Its unique contribution lies in revealing how rising environmental losses can function as an endogenous driver of collective governance, indicating that stronger risk disclosure and information feedback can effectively advance cross-regional emission-reduction coordination.

The array is sequentially set to satisfy the conditions in Corollary 7 and Corollary 8, and 50 evolutions are performed from their respective starting strategies. The results of the experiment are shown in Fig. 10.

Figure 10 indicates that the game system satisfies condition ①: when $C_{kh} - C_{kl} - M_q < B_q$, $C_{ph} - C_{pl} > S_T$, there exists an evolutionarily stable point E_1 (0, 0, 0), with evolutionary stable strategy combinations (negative participation in cross-regional collaborative emission reduction for all parties), consistent with the conclusion of Corollary 7. Regarding condition ②: when $C_{kh} - C_{kl} - M_q > B_q$, $C_{ph} - C_{pl} > M_p$, $C_g + M_p < T_g$, the system exhibits an

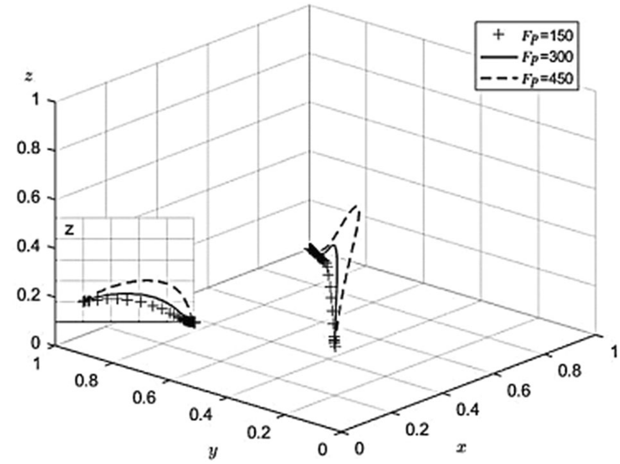

Fig. 7 The impact of fines (F_1) for construction enterprises' negative participation in cross-regional collaborative emission reduction. Simulation results show how penalty intensity affects enterprises' strategic adjustment.

evolutionary stable point E_5 (1, 1, 0), indicating the construction enterprises, social public, and local government's evolutionarily stable strategy combinations (active participation in cross-regional collaborative emission reduction for the construction enterprises and the public, and negative participation for the local governments). Local governments play a crucial role in the development of the construction industry. With increasing environmental awareness, cross-regional collaborative emission reduction has become integral to the industry's sustainable development. However, conflicts of interest often arise among construction enterprises, the public, and local governments, leading to negative participation by all parties in cross-regional collaborative emission reduction, posing a serious challenge to the industry's green development.

Therefore, local governments should fully consider the interests of construction enterprises and the public in promoting collaborative emission reduction in the construction industry. This entails understanding the practical challenges and needs of construction enterprises regarding emissions reduction, as well as the public's environmental concerns and expectations. Only full respect for and balance of the interests of all parties can establish an effective collaborative emissions-reduction mechanism and avoid negative participation due to conflicting interests.

This study examines the operational principles of the collaborative emission-reduction mechanism in the construction industry through numerical simulations and stability analysis of the equilibrium point in the three-party game system. Simulation results indicate that maximizing emission-reduction benefits in the construction industry requires comprehensive consideration of all parties' interests and the development of a reasonable collaborative mechanism for emission reduction. The stability analysis of the equilibrium point of the three-party game system reinforces this conclusion.

The findings provide robust theoretical underpinnings and practical guidance for developing a collaborative emissions-reduction mechanism for the construction industry that involves government, enterprises, and the public. Establishing a tripartite is essential for realizing green construction. The path to collaborative emission reduction in the construction industry will mature over time through comprehensive consideration of all parties' interests, enhanced communication and collaboration, and the formulation of scientifically sound policies and measures.

General discussion

Coordination dynamics and stability in tripartite cross-regional emission governance

This study develops a three-party game-evolution model to examine the dynamics of strategic choices and mutual influences among enterprises, the government, and the public, each acting in pursuit of their respective interests.

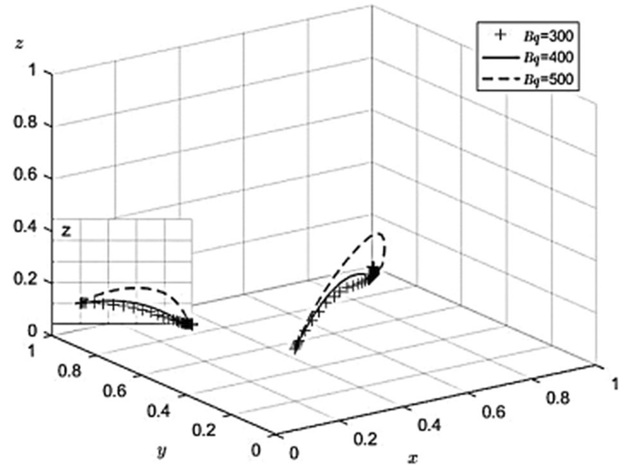

Fig. 8 The impact of ecological compensation (H_1) for construction enterprises. Simulation results show how compensation levels influence enterprises' strategic choices over time.

Numerical simulation visualization is used to illustrate the impact of key parameters on the evolutionary trajectory and to provide insights into multi-stakeholder emission-reduction efforts. The main findings and implications are as follows.

Heterogeneous coordination pathways by the leading actor

When incentives primarily target enterprises, the share of enterprise participation rises monotonically with increasing incentive intensity, and the system converges to an enterprise-centered coordination pattern. Government and public participation decline at the margin, consistent with firms' internalizing abatement benefits and relying less on external administrative impetus. By contrast, elevating public-side incentives significantly increases public participation and, through social oversight and reputational pressure, indirectly induces cooperative behavior by enterprises, while government participation remains comparatively stable. The former pathway reflects cost-benefit internalization with faster convergence and lower governance frictions. The latter strengthens transparency and social constraint, enhancing the credibility and durability of cooperation. Policy instruments can thus promote coordination along either an "enterprise-empowerment" path or a "bottom-up mobilization" path. However, the associated convergence speed, resource requirements, and governance foundations differ and should be matched to the context.

Thresholds and nonlinear policy responses

The model uncovers effective bandwidths and inflection points for core instruments. Raising penalty severity from 150 to 300 effectively curbs non-compliant enterprise behavior. Further escalation to 450 produces a rise-then-fall in government participation, indicating that enforcement burdens and execution frictions can erode long-run cooperation (Fig. 7). Increasing ecological compensation from 150 to 300 activates all three actors. Beyond 450, government participation weakens, exhibiting an inverted-U marginal effect and potential moral hazard (Fig. 8). Heightened salience of environmental losses, from 300 to 450 and 600, accelerates public and government participation, and once a critical threshold is crossed, enterprises shift from waiting to cooperation (Fig. 9). Clear, timely, and verifiable risk disclosure thus functions as a trigger for collective action. In contrast, intermediate risk levels tend to sustain delay. Overall, the linear "more-is-better" intuition does not hold. Optimal ranges, turning points, and instrument-execution matching determine sustainable cooperation.

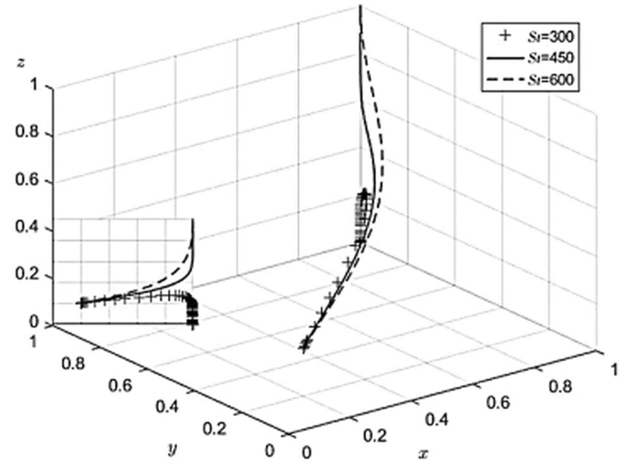

Fig. 9 The impact of environmental losses (L_2) caused by carbon emissions from the construction industry. Simulation results show how environmental loss levels affect the evolutionary trajectories of strategies.

Incentive-cost balance shapes attainable and stable steady states

Participation is highly sensitive to each actor's cost-benefit profile. As the unit administrative cost for the government rises from 100 to 300, government participation declines sharply and, through diminished institutional support, depresses enterprise and public participation (Fig. 6). Moderate ecological compensation alleviates fiscal pressure and signals support. However, excessive compensation diminishes governance momentum and long-term engagement (Fig. 8). Evolutionary stability analysis indicates convergence to either a zero-participation steady state or a partial-cooperation state, characterized by active enterprises and public but inactive government. A fully active steady state does not emerge within the tested parameter space (Fig. 10). These patterns imply that without calibrated incentives and equitable benefit-sharing, at least one actor will persistently opt out, undermining stability. Conversely, fine-tuning subsidies, penalties, and compensation, in conjunction with fair cost-benefit sharing, substantially improves the attractiveness and robustness of joint action.

Existing regional practice also suggests that, when cooperative gains are allocated fairly, coordinated abatement delivers clear advantages over fragmented action in both cost efficiency and stability (Liu et al. 2022). Moreover, within cap-and-trade and related market arrangements, simultaneously lowering firms' abatement costs and strengthening governmental incentives and constraints markedly improves the stability of joint mitigation (Yu et al. 2022b).

Institutional supply and coordination capacity are binding constraints on durable cross-regional cooperation

Although "enterprise-first" and "public-first" pathways can generate favorable short-run dynamics under generous incentives, sustained cross-jurisdictional cooperation ultimately depends on unambiguous policy signals, harmonized rules, and commensurate execution and coordination on the government side. Across comparative scenarios, weak institutional supply systematically steers the system toward non-cooperative traps. In contrast, unified standards, verifiable results-based arrangements, and mechanisms for sharing administrative costs accelerate entry into and enhance the resilience of the high-participation basin (Fig. 10).

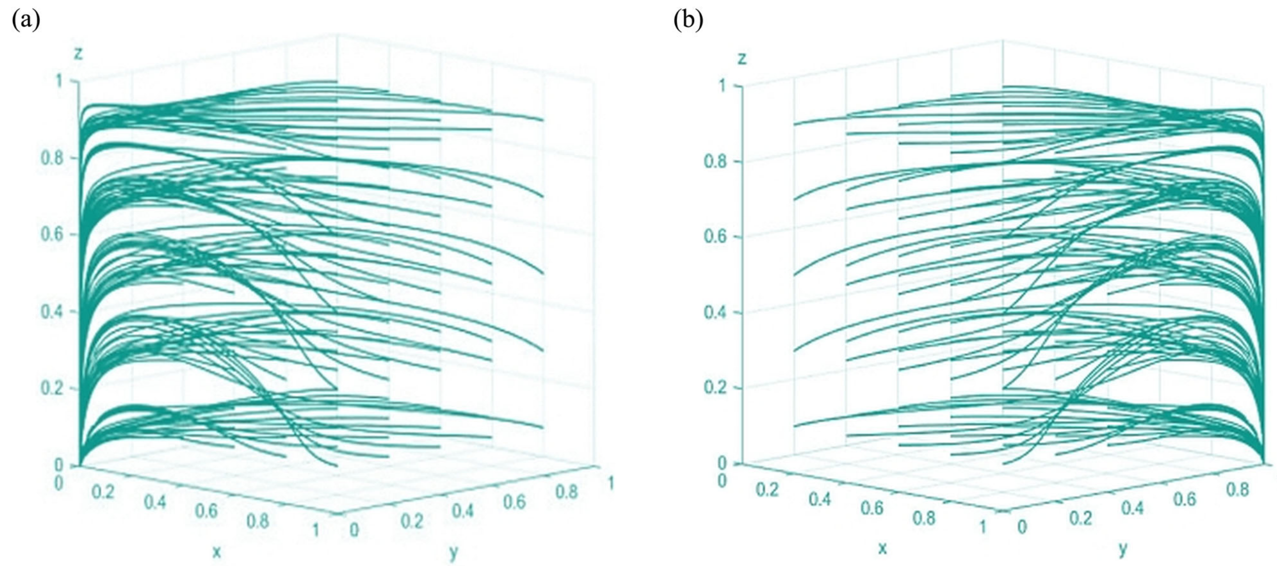

Fig. 10 Schematic diagram of evolutionary results. a Array 1: Evolutionary trajectories under Array 1 (Scenario satisfying Corollary 7), converging to (0, 0, 0); **b** Array 2: Evolutionary trajectories under Array 2 (Scenario satisfying Corollary 8), converging to (1, 1, 0).

Cross-regional collaborative carbon reduction strategies for the construction industry

Intergovernmental coordination for cross-regional emission reduction

To enhance the institutional effectiveness of cross-regional collaboration in the construction sector of the Guangdong-Fujian-Zhejiang coastal urban belt, a centrally guided, unified low-carbon architecture should be established. It includes the dynamic updating of sectoral standards, a monitoring, reporting, and verification system, and the mutual recognition of interprovincial and intercity results. Additionally, it involves integrating cross-regional coordination performance into local governance assessments to counterbalance single-metric growth incentives. In light of the model and simulation results, which identified "cost-dominated" zones in which rising government costs trigger cascading strategic withdrawal, an interjurisdictional burden-sharing fund should be established alongside administrative cost-hedging arrangements to stabilize cooperation. Priority support should be directed toward joint enforcement initiatives, data interoperability, and high-impact retrofit projects. Fiscal incentives should be directly linked to verified lifecycle abatements delivered across jurisdictions. They should include explicit caps, tapering schedules, and periodic recalibration of baselines and verification protocols to reflect the observed policy's "effective range" and policy-response inflection points and to pre-empt moral hazard. A unified regional platform for construction-sector carbon and energy data should enable real-time alerts, parallel benchmarking, and traceable supervision to support joint prevention and control, reduce information asymmetries and cross-border regulatory arbitrage, and internalize spatial externalities. Within a common rules framework, a light-weight interprovincial secretariat should clarify mandates and dispute-resolution procedures while preserving space for locally differentiated strategies, thereby achieving sustainable coordination under the model's stability conditions.

Enterprise-government coordination in the construction sector

Policy mixes should be calibrated to an enterprise-led pathway. On the incentive margin, it can stage and differentiate direct enterprise incentives to target processes with high marginal abatement costs and strong cross-regional spillovers, thereby fostering self-sustaining internalization of abatement benefits. On the constraint margin, it can set sanction intensity within empirically identified effective bandwidths and co-provide standardized compliance guidance, on-site audit toolkits, and correction channels to avoid enforcement overload and the observed "rise-then-fade" dynamics in governmental participation. Market mechanisms should shift carbon performance upstream by embedding carbon-intensity thresholds, process controls, and acceptance rules into green procurement and EPC contract management, thus relocating incentives and constraints to the supply chain. Financially, it can consider applying interest-subsidized loans, energy-performance contracts, and carbon-asset custodianship to implement verified results-based payments, thereby lowering financing barriers, improving cash-flow certainty, and accelerating efficiency retrofits. Technically and operationally, it can prioritize high-return interventions in envelopes and end-use systems, while deploying building-level monitoring, optimization, and load shifting, so that continuous abatement becomes measurable, verifiable, and billable performance. For cross-regional projects, it can allocate compensation and fiscal settlement strictly in accordance with verified abatement. Such measures can prevent double-subsidization and adverse incentives, improve fiscal efficiency and equity, and ensure that ecological compensation genuinely recycles across jurisdictions, closing the loop with incentive, sanction, and contract mechanisms.

Society-government coordination and public-facing mechanisms

Public participation should be institutionalized through a standing channel centered on well-designed public incentives, routine disclosure, and accessible feedback, thereby activating social oversight and reputational constraints that induce firms to adjust strategies. Based on the risk-salience thresholds identified by simulations, a tiered regime for risk communication and information disclosure should be established. It should include project and district-level dashboards of environmental loss indicators to encourage actors to move from inaction to coordination at earlier stages. Civil-society organizations and professional associations should be supported in conducting independent monitoring, technical outreach, and community co-governance projects, thereby strengthening the interface through which public preferences enter policy processes and improving comprehensibility and acceptability. Implementation should prioritize building-centered community demonstrations, distributed PV and storage, envelope retrofits, heat pumps, and intelligent energy management. These measures can translate dispersed participation into measurable, verifiable, and payable abatement, and close the loop among incentives, constraints, and social supervision under unified MRV and results-based frameworks. Such arrangements align with the model's public-driven mechanism and risk-threshold effects, which are expected to improve the long-term stability and performance of cross-regional coordination.

Conclusion

This study developed an innovative tripartite evolutionary game model encompassing local governments, construction enterprises, and the public. The strategic decisions and interactions under various scenarios were simulated by adjusting parameters and initial conditions. The approach aimed to validate the model's reliability and applicability, thereby supporting the implementation of collaborative emission-reduction mechanisms in the construction industry across regions. The ultimate goal is to drive the urban agglomeration toward environmental protection and sustainable development. The main conclusions of this study are as follows.

(1) Balanced stakeholder interests for effective collaboration. The model emphasizes that fully balancing and respecting the interests of local governments, construction enterprises, and the public is vital to successful emission-reduction cooperation. Only by aligning the interests of stakeholders can an effective collaborative emission reduction mechanism be established, thereby avoiding "negative participation".

(2) Enterprise participation hinges on cost and cooperation. Construction enterprises are highly sensitive to the cost gap between actively reducing emissions and refraining from such efforts. Simulation results show that the smaller the cost disparity, the more likely enterprises are to engage in cross-regional emission reduction actively. Moreover, companies are more inclined to participate when they expect local governments and the public to cooperate as well, indicating a positive feedback loop in which each party's willingness reinforces the

others'.

(3) Public engagement driven by incentives and perceived impact. Public willingness to participate in emission reduction correlates positively with government incentives and the perceived impact of construction-related emissions on their lives. Increased incentives from local authorities boost enthusiasm for public participation. However, if governments and enterprises are already cooperating closely, the public may treat non-participation as a stable strategy unless there are active efforts to engage them. This highlights the need for policies that continually encourage public involvement, even when other stakeholders are collaborating.

(4) Local government participation and the role of penalties. The likelihood of local governments actively engaging in cross-regional emission reduction increases when strong incentive and penalty structures are in place. The model suggests that local governments are more willing to cooperate if construction enterprises face substantial penalties or eco-compensation fees for failing to reduce emissions, and if local officials themselves face penalties imposed by the central government for failing to act. Additionally, like enterprises, local governments are more proactive when they anticipate active participation from businesses and the public, creating a mutually reinforcing commitment to collaboration.

(5) Optimizing incentive structures to promote cooperation. The study highlights the importance of designing incentive systems such that the rational choice for all parties is to cooperate in emission reduction. In practice, this means ensuring that the net benefits of active participation outweigh those of non-participation for both enterprises and the public. For example, government subsidies minus any required eco-compensation should make the cost of participating more attractive to enterprises, and the personal cost for the public to engage in emission reduction should be lower than the expected harm from unchecked emissions. Furthermore, stronger penalties from higher authorities can motivate local governments to adopt active emission-reduction strategies, making collaborative efforts the stable and dominant strategy for everyone.

In conclusion, these findings provide a robust theoretical and practical foundation for implementing collaborative emission-reduction mechanisms in the construction industry. The proposed tripartite game model deepens the understanding of multi-stakeholder dynamics and offers valuable insights for policymakers. In particular, it guides governments and enterprises in formulating effective cross-regional emission-reduction policies, highlighting that establishing strong tripartite collaboration is essential to achieving green construction. Over time, such a collaborative framework, grounded in aligned interests, active communication, and science-based policies, will drive the urban agglomeration toward environmental sustainability.

Acknowledging the limitations, this study recognizes that research on cross-regional collaborative emission reduction in the construction industry is still in its infancy, with relatively limited findings. Consequently, this paper focuses on a three-party game model involving "enterprises-government-public". Future investigations could expand to include additional stakeholders and strive to develop optimal solutions that balance environmental concerns, costs, and other objectives. Additionally, while the research scope is confined to the urban agglomeration, future endeavors could extend to larger geographical areas to enhance the generalizability of the methods and findings.

Despite these limitations, the study provides theoretical insights to help governments and enterprises develop effective policies and guidelines. It also contributes to advancing the collaborative development strategy of the construction industry in the coastal urban agglomeration. Theoretical contributions include laying the groundwork for research methodologies and ideas in cross-regional collaborative emission reduction in the construction sector. From a practical standpoint, the analysis provides a scientific basis for tailoring energy-saving and emission-reduction policies within these cities, thereby aiding their sustainable development efforts.

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Declarations

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