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Research on multi-stage strategy of low carbon building material's production by small and medium-sized manufacturers: A three-party evolutionary game analysis

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Using green technology by building materials manufacturers to produce low-carbon building materials is an effective way to control carbon emissions and promote traditional industries' green and low-carbon development. Based on the government, small and medium-sized building materials manufacturers, and scientific research institutes, this paper sets 15 variables that affect the strategy selection of game participants, establishes an evolutionary game model under the constraint of the carbon tax, explores the behavioral strategies of the three parties in the industry life cycle to produce low-carbon building materials, and analyzes the sensitivity of critical factors. Results: The government plays a leading role in the initial stage, which is gradually replaced by the market-leading mechanism as the low-carbon building materials industry develops to maturity. The government's decision-making behavior is almost unaffected by the two, and appropriate subsidies and carbon tax penalties at each stage of the industry life cycle can help improve the enthusiasm of the other two parties to participate in low-carbon behavior. Establishing a reasonable income distribution coefficient between small and medium-sized building materials manufacturers and scientific research institutes is more conducive to speeding up the stable state than transferring and selling technology.

KEYWORDS

industry life cycle, low-carbon building materials, incentive policy, income distribution coefficient, evolutionary game

1 Introduction

With urbanization's rapid development, global warming has been widely concerned (Chen et al., 2017). Carbon emissions from energy consumption are a vital contributor to global warming, and countries are now committed to achieving carbon neutrality (Teng and Pan, 2020). The building materials industry is one of the largest industrial sectors of carbon dioxide emission, which accounts for more than 10% of the national carbon emission. The building materials industry shouldered the historical responsibility (Jin et al., 2021).

As the national carbon market coverage expands to the building materials industry, it will undoubtedly impact building materials enterprises (Wang et al., 2022). It is found that compared with the whole process of producing ordinary cement, the entire process of making slag Portland cement can realize saving and reduce carbon emissions by 236 kg/t (carbon emission reduction by 26%) (Song et al., 2012). Compared with the replacement of natural aggregate, biomass recycled aggregate synthesized from agricultural waste coconut shells can reduce CO_2 emissions by 2% (Ni et al., 2022). If the fly ash-to-cement ratio is partially replaced, the carbon emission can be significantly reduced (Khan et al., 2020). The above literature and research results have proved that green building materials will reduce carbon and bring higher efficiency. Thus, promoting the green and low-carbon transformation of the building materials industry is one of the significant measures to control carbon emissions and cope with global climate change (Jiang et al., 2022).

In the past decade, to achieve carbon reduction targets, governments in many countries have established relevant supervision institutions (Shen et al., 2016). Governments have adopted corresponding incentive measures, such as financial subsidies, carbon tax penalties, market guidance, and technical support, to encourage enterprises to pay attention to green products and continuously improve innovation capacity (Liu et al., 2022). Many scholars have conducted in-depth studies on the rationality and effectiveness of these policies. For example, Fan et al. (2022) build different information interaction mechanisms based on the evolutionary game model of complex networks to study the dynamic impact of government policies on the diffusion of green innovation in enterprises. Olubunmi et al. (2016) show that incentives can be divided into external and internal stimuli and further discuss the effectiveness of the current incentive mechanism. Fan and Hui. (2020) used quantitative methods to illustrate motivation points and participants' strategic changes.

In the research and development of small and medium-sized enterprises (SMEs), due to information asymmetry and substantial resource constraints, independent innovation has uncertain risks (Barbaroux, 2014). Therefore, R&D cooperation with research institutes is crucial to overcome the lack of internal business resources of SMEs and improving their innovation ability and competitiveness (Aristei et al., 2016). At the same time, to guarantee the respective rights and interests of SMEs and the research institute, a perfect contract system should be established between the two parties. In this research field, Zhou and Cai. (2016) study the operation risk and prevention strategies of the public service contract purchase and put forward healthy and sustainable development suggestions for public service contract purchase in China. Li. (2016) theoretically discussed the structural characteristics and element composition of the governance mechanism of the "contract system".

Although the existing literature has carried out theoretical research on Low-carbon building materials (LBM) production using evolutionary game theory (EGT), it also provides ideas for reference for the analysis of this paper. However, the research on the four-stage production LBM behavior strategy based on the industry life cycle (ILC) is still lacking and still in its infancy. In particular, systematic studies incorporating SMEs' limitations into EGT are less well known. At the same time, the R&D cooperation attitude of the contract system of research institutes is included in the variable hypothesis, which distinguishes other R&D cooperation modes and provides a quantitative basis for the distribution of innovation income. Under the assumption of limited rationality and finite assumptions, this work applies EGT to progressively arrive at an ideal equilibrium state through communication and cooperation of all parties and suggests a number of equilibrium conditions and policy recommendations. It is hoped that the research in this paper will work as a theoretical guide for the government guides small and medium-sized (SM) building materials manufacturers to produce LBM by forecasting the development history of SM building material manufacturers in the LBM industry. Therefore, by establishing a triple evolutionary game model of the government, SM materials manufacturers, and scientific research institutes, this paper analyzes the basic conditions for the tripartite subjects to evolve to the equilibrium state based on ILC to deeply explore the forward-looking issue of how small and medium-sized building materials manufacturers can independently transform in the LBM industry to maintain their stable development.

2 Literature review

2.1 Effect of government incentive policies

The government has much capacity to encourage the green growth of the building industry because it is the prominent owner of that sector (He and Chen, 2021). Studies in the past have explored various aspects of government incentive programs, including literature reviews (Olubunmi et al., 2016), strategic decisions (Hu et al., 2020), cost-benefit analyses (Wu and Ma, 2022), and non-cooperative games (Zhou et al., 2022). Through a thorough literature analysis, Wasserbaur et al. (2022) extensively defined the connection between governmental initiatives and company models. Green development is encouraged by government subsidies, and contributions to diverse causes will have a variety of positive societal effects. The incentive effect better serves consumers than developers (He and Chen, 2021). In addition, the way incentive programs are constructed will have both direct and indirect impacts on stakeholders' choice of government. Fan and Wu. (2020) created a causal loop diagram to illustrate government incentives and evaluated the cost-effectiveness of government in terms of importance and money value using transaction cost analysis and hierarchical analysis. It was discovered that transaction costs—such as those associated with monitoring, approval, coordination, and other processes—are factors that influence how governments make decisions. Under the non-cooperative game, Amiri-Pebdani et al. (2022) constructed a Stackelberg model with the government as the dominant player and manufacturers and retailers as the followers to analyze the impact of government environmental incentives on firms' green technology innovation.

However, little research has been conducted on stakeholder behavior and decision-making under the restrictions of the carbon tax or the effects of government incentives at various stages within the ILC (Zhou et al., 2022). Due to this, evolutionary game theory modeling is a well-known and effective method for evaluating stakeholders' choices (Shan et al., 2021).

2.2 Enterprise green technology innovation

In the past decade, stakeholder behavior in green technology innovation has been a concern, and green technology investment has been the focus of scholars' research. To determine the best course of action for investing in green technology to reduce carbon emissions, Hussain et al. (2022) suggested considering the monopoly market of carbon-emitting businesses and using an optimization model based on simulation. Government management policies and corporate green technology innovation are intimately intertwined, and Zhou et al. (2022) assessed the long-term effect of green technology advancement on renewable energy consumption under government supervision. In their study, Mohsin et al. (2021) compared the equilibrium solutions of differential games played under centralized and decentralized decision-making under government control and concluded that under centralized decision-making, the level of green technology and the total profit of green channels were higher. To identify an efficient market regulatory system to encourage the development of green technology innovation, Li and Gao. (2022) created a three-way evolutionary game model between two types of enterprises with varied R&D capabilities and banks. As a foundation for how governments can create the best subsidy plans to encourage managers' green technology innovation behavior, Liu et al. (2021) explored how managers can achieve the best green technology investment-production strategies in the supply chain.

In contrast, previous studies have ignored many SM enterprises and their technical limitations, which need to be developed with innovative institutions. To fill this research gap, this paper discusses the evolution mechanism of the ILC low-carbon transition from the perspective of government subsidies and attitudes of research institutes.

2.3 Study government and enterprise behaviors under environmental regulation of carbon emission reduction by using traditional game

In introducing game theory to study economic problems, the government and enterprises are regarded as game subjects to review the strategic choices of both sides. Zhao et al. (2012) applied game theory to non-cooperative game analysis to examine the methods manufacturers utilized to lower environmental risks and carbon emissions over the material life cycle. To determine the applicable indirect green tax for the Iranian economy, Norouzi et al. (2022) develop a suitable model and employ a game-theoretic methodology. According to Ji. (2021) research, creating a global carbon emissions trading model is a successful strategy for reducing global warming using market processes. By considering various environmental regulatory measures, Yenipazarli. (2016) investigates the pricing game between enterprises and their economic or environmental advantages. To study how government environmental behavior affects business green technology innovation, Madani and Rasti-Barzoki. (2017) created a Stackelberg model with the government as the leader and manufacturers and retailers as the followers. By developing a three-stage Stackelberg model, Long et al. (2019) explored the effect of governmental behavior policies on corporate strategy.

As a result, previous research has primarily used the Gounod and Stackelberg game model to examine the behavioral tactics used by businesses subject to environmental legislation. In contrast to the assumption of completely rational conduct in game theoretic models, the assumption of bounded rationality in evolutionary game theory is more pertinent (Madani and Rasti-Barzoki, 2017).

In conclusion, to address the previous research gaps, this paper will fill the aforementioned gaps from the following points: firstly, this paper takes into account the limited innovation capacity of low-carbon technologies and includes both SM building material manufacturers and research institutes in the evolutionary game model, and incorporates the revenue allocation coefficients into the variable assumptions in order to maintain the stability of their cooperation. Second, the four stages of ILC theory are introduced into the EGT. Based on the analysis of government subsidies and carbon tax, the influence of other influencing factors on the evolution of tripartite subjects is further explored.

Drawing on EGT, the three objectives of this study are stated as follows:

1) To reduce carbon emissions, should the government provide subsidies to SM building material manufacturers to encourage the production of LBM? Or would it be more effective to impose a so-called carbon tax on products that harm the environment?
2) What is the government's role in each stage of ILC for low-carbon building materials?
3) Under different carbon tax and subsidy combinations, is the size of the income distribution coefficient between SM building material manufacturers and scientific research institutes conducive to encouraging manufacturers to produce LBM?

3 Evolutionary game model

3.1 Assumptions

Hypothesis 1: As shown in Figure 1, this study involves three participants: the government, SM building material manufacturers, and scientific research institutes. The strategy of government departments is K =(absolute policy support and relative policy support). Absolute policy support means the government promotes building material manufacturers to produce LBM through strict legislation, law enforcement, and effective incentive measures. Relative policy support means that the government follows the original standard market rules. SM building material manufacturers' strategy is M = (low carbon building material production and production of ordinary building materials), the system of scientific research institutes is N = (a positive attitude, and the positive perspective attitude is to point to actively joining in the transformation of LBM by signing a contract manufacturer and mutual benefit, to provide the technology, a partial perspective refers to directly transfer the technology to use sales to SM building material's manufacturers.

Hypothesis 2: The probability of absolute policy support by the government is $x\,(0 \le x \le 1)$, the likelihood of relative policy support is $1 - x$, the possibility of low carbon material production by SM building material's manufacturers is $y\,(0 \le y \le 1)$, the probability of ordinary material production is $1 - y$, the likelihood of positive attitude of scientific research institutes is $z\,(0 \le z \le 1)$, and the possibility of partial perspective is $1 - z$.

Hypothesis 3: The cost of absolute policy support for the government is Cp, including the cost of policy supervision and policy-making, and the benefit of absolute policy support is Rp, the improvement of government credibility and sustainable economic

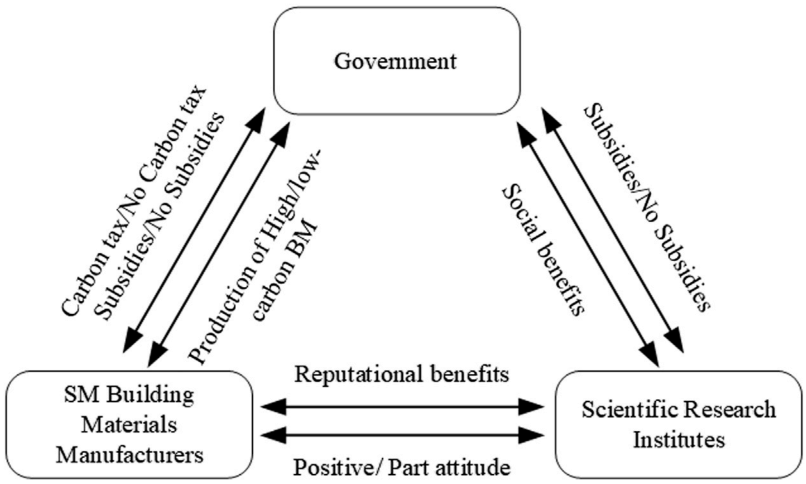

FIGURE 1
Game relationship among government, SM building material manufacturers, and scientific research institutes.

TABLE 1 Description of significant parameters.

Parameter	Descriptions
x	The probability of absolute government policy
y	Probability of LBM production by SM building material manufacturers
z	The probability of a positive attitude in a scientific institution
Rn	Revenue from HBM production for SM building material manufacturers
Rm	SM building material manufacturers' production of LBM revenue
Rp	The benefits of an absolute government policy
Rq	The benefits of the government's implementation of relative policies
Rs	Revenue from the sale of low-carbon technologies by research institutions
a	SM building material manufacturers and scientific research institutes signed the contract after the income distribution coefficient
Cn	Cost of HBM production for SM building material manufacturers
Cm	Cost of LBM production for SM building material manufacturers
Cp	The cost of absolute government policy
Cq	The cost to the government of implementing relative policies
Cr	The cost of a positive attitude in research institutions
Cs	The cost of partial attitudes of research institutes
Iu	Subsidies to research institutes under absolute government policy
Ie	Government subsidies for SM building material manufacturers under the absolute policy
D	The punishment of HBM production by small and medium building material manufacturers under absolute government policy

development. Under the corresponding policy support, the government's cost is Cq and its benefit is Rq. Subsidize the research institutes with Iu.

Hypothesis 4: SM building materials manufacturers do not have strong technical conditions and the ability to develop low-carbon and environmental protection alone, so they can only buy from scientific research institutes or sign cooperation contracts. The revenue of LBM production is Rm and the cost is Cm. The payment of producing common building materials (HBM) is Rn and the cost is Cn. For the production of LBM, when the government implements absolute

TABLE 2 Payoff matrix of the three-party game mode.

The government	Scientific research institutes	SM building material manufacturers	
		Production of LBM (y)	Production of HBM $(1-y)$
Absolute policy (x)	positive attitude (z)	$Rp - Iu - Ie - Cp$	$Rp - Cp - Iu + D$
		$Rm(1-a) + Ie - Cm$	$Rn - Cn - D$
		$Rm\,a + Iu - Cr$	$Iu - Cr$
	Negative attitude $(1-z)$	$Rp - Iu - Ie - Cp$	$Rp - Cp + D$
		$Rm + Ie - Cm - Rs$	$Rn - Cn - D$
		$Rs + Iu - Cs$	0
Relative policy $(1-x)$	positive attitude (z)	$Rq - Cq$	$Rq - Cq$
		$Rm(1-a) - Cm$	$Rn - Cn$
		$Rm\,a - Cr$	$-Cr$
	Negative attitude $(1-z)$	$Rq - Cq$	$Rq - Cq$
		$Rm - Cm - Rs$	$Rn - Cn$
		$Rs - Cs$	0

policy, the government will give the SM building materials manufacturer a subsidy Ie, but for the production of HBM, the government will impose a D fine on the SM building materials manufacturer. In implementing the relative strategy, the government and SM building materials manufacturers do not give subsidies and penalties.

Hypothesis 5: The cost of implementing part of the attitude of scientific research institutes is Cs, including the expenses of R&D personnel and management personnel and the profit of selling technology to SM building materials manufacturers is Rs. With the support of government policies on absolute, scientific research institutes to implement positive attitude is the cost of Cr, include the costs of research and development personnel, management personnel, and the cost of bidding procedures, including signing a contract, after signing a contract with SM building materials manufacturers, according to the income distribution coefficient of a to share the profits, and Iu can receive government subsidies. The symbols of parameters and variables and their meanings are shown in Table 1.

3.2 Establishment of income model

The payoff matrix of the evolutionary game model can be obtained according to the basic assumptions and the setting of the payoff and loss parameters, as shown in Table 2.

3.2.1 Expected revenue for the government

As shown in Table 2, when the government adopts an absolute incentive policy ($k1$), the expected revenue of the government (E_{k1}) can be measured by Equation (1). When the government adopts a relative incentive policy ($k2$), the anticipated payment of the government (E_{k2}) can be calculated by Equation (2). The government's average expected return is E_k.

$$\begin{aligned} E_{k1} = & -yz(Rp-Iu-Ie-Cp)+(1-y)z(Rp-Cp-Iu+D) \\ & +y(1-z)(Rp-Iu-Ie-Cp)+(1-y)(1-z)(Rp-Cp+D) \end{aligned} \tag{1}$$

$$\begin{aligned} E_{k2} = & \; yz(Rq-Cq)+z(1-y)(Rq-Cq)+y(1-z)(Rq-Cq) \\ & +(1-y)(1-z)(Rq-Cq) \end{aligned} \tag{2}$$

$$E_k = xE_{k1} + (1-x)E_{k2} \tag{3}$$

According to Equations 1–3, the dynamic replication equation of the government is denoted as $F(x)$.

$$\begin{aligned} F(x) &= \frac{dx}{dt} = x(Ek1 - Ek) \\ &= x(x-1)\begin{pmatrix} Cp - Cq - D - Rp + Rq + D^*y+ \\ Ie^*y + Iu^*y + Iu^*z - Iu^*y^*z \end{pmatrix} \end{aligned} \tag{4}$$

Let's set it equal to 0: $x=0, x=1, y=\frac{Cp-Cq-D-Rp+Rq+Iu^*z}{Iu^*z-D-Ie-Iu}$
Taking the first derivative leads to the following:`

$$\frac{dF(x)}{dx} = (2x-1)\begin{pmatrix} Cp - Cq - D - Rp + Rq + D^*y+ \\ Ie^*y + Iu^*y + Iu^*z - Iu^*y^*z \end{pmatrix} \tag{5}$$

According to the stability theorem of differential equations, the probability of the government choosing absolute policies in a stable state must meet the following requirements: $F(x)=0$ and $\frac{dF(x)}{dx}<0$. We can get the following proposition.

Proposition 1

1) If $y = y^* = \frac{Cp-Cq-D-Rp+Rq+Iu^*z}{Iu^*z-D-Ie-Iu}$ (Figure 2A), then $F(x) \equiv 0$. This means that no matter takes any value (whether to adopt an incentive policy or not), the game is stable, and the government will get the same revenue.
2) If $y < \frac{Cp-Cq-D-Rp+Rq+Iu^*z}{Iu^*z-D-Ie-Iu}$ (Figure 2B), then $\left.\frac{dF(x)}{dx}\right|_{x=0} < 0, \left.\frac{dF(x)}{dx}\right|_{x=1} > 0$ In this case, $x=0$ is the steady state, and the government tends to implement relative policies.

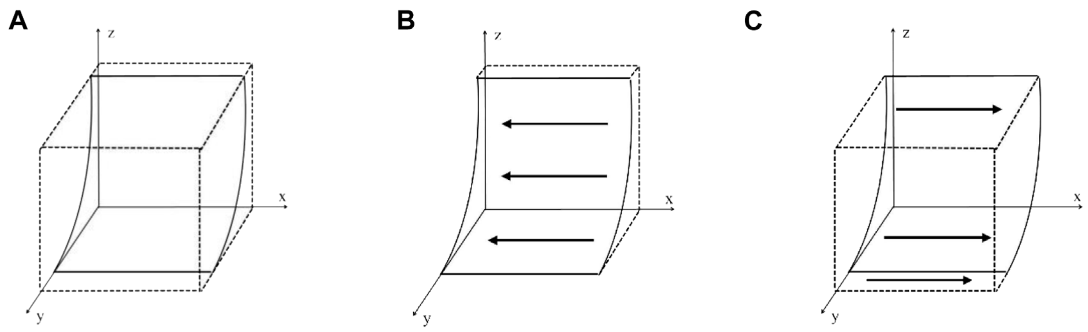

FIGURE 2
Dynamic evolution phase diagrams of government.

3) If $y > \frac{Cp-Cq-D-Rp+Rq+Iu^*z}{Iu^*z-D-Ie-Iu}$ (Figure 2C), then $\frac{dF(x)}{dx}\big|_{x=0} > 0$, $\frac{dF(x)}{dx}\big|_{x=1} < 0$. In this case, $x = 1$ is the steady state, and the government tends to implement absolute policies.

3.2.2 Expected revenue for SM building material manufacturers

SM building materials manufacturers produce LBM $(m1)$, and the expected revenue of medium and small building materials manufacturers (E_{m1}) can be measured by Equation 6. SM building materials manufacturers produce HBM $(m2)$, and the expected revenue of SM building materials manufacturers (E_{m2}) can be measured by Equation 7. The average expected revenue of SM building materials manufacturers is E_m.

$$\begin{aligned} E_{m1} = {} & xz[Rm(1-a)+Ie-Cm]+x(1-z)(Rm+Ie-Cm-Rs) \\ & +(1-x)z[Rm(1-a)-Cm]+(1-x)(1-z)(Rm-Cm-Rs) \end{aligned} \tag{6}$$

$$\begin{aligned} E_{m2} = {} & xz(Rn-Cn-D)+x(1-z)(Rn-Cn-D) \\ & +(1-x)z(Rn-Cn)+(1-x)(1-z)(Rn-Cn) \end{aligned} \tag{7}$$

$$E_m = yE_{m1} + (1-y)E_{m2} \tag{8}$$

Based on Equations 6–8, the dynamic replication equations of SM building material manufacturers are denoted as $F(y)$.

$$\begin{aligned} F(y) &= \frac{dy}{dt} = y(Em1 - Em) \\ &= y(y-1)\begin{pmatrix} Cm - Cn - Rm + Rn + Rs \\ -Dx - Iex - Rsz + aRmz \end{pmatrix} \end{aligned} \tag{9}$$

Let's set it equal to 0: $y = 0, y = 1, z = \frac{Cm-Cn-Rm+Rn+Rs-x(D+Ie)}{Rs-aRm}$

Taking the first derivative leads to the following:

$$\frac{dF(y)}{dy} = (2x-1)(Cm - Cn - Rm + Rn + Rs - Dx - Iex - Rsz + aRmz) \tag{10}$$

According to the stability theorem of a differential equation, the probability of LBM production by SM building material manufacturers in a stable state must meet the following requirements: $F(y) = 0$ and $\frac{dF(y)}{dy} < 0$. We can get the following proposition.

Proposition 2

1) If $z = z^* = \frac{Cm-Cn-Rm+Rn+Rs-x(D+Ie)}{Rs-aRm}$ (Figure 3A, then $F(y) \equiv 0$. This means that no matter the value (whether LBM is produced or not), the game is stable, and SM building material manufacturers will get the same income.
2) If $z < \frac{Cm-Cn-Rm+Rn+Rs-x(D+Ie)}{Rs-aRm}$ (Figure 3B), then $\frac{dF(y)}{dy}\big|_{x=0} < 0$, At this time, $y = 0$ is a stable state, SM building material manufacturers tend to produce HBM.
3) If $z > \frac{Cm-Cn-Rm+Rn+Rs-x(D+Ie)}{Rs-aRm}$ (Figure 3C), then $\frac{dF(y)}{dy}\big|_{x=0} > 0$, At this time, $y = 1$ is a stable state, SM building material manufacturers tend to produce LBM.

3.2.3 Expected revenue for research institutes

When the research institute has a positive attitude $(n1)$, the expected revenue of the research institute (E_{n1}) can be measured by Equation (11). When the scientific research institute has a partial attitude $(n2)$, the expected revenue of small and medium-sized building materials manufacturers (E_{n2}) can be measured by Equation (12). The average expected revenue of a research institute is E_n.

$$\begin{aligned} E_{n1} = {} & xy(aRm + Iu - Cr) + x(1-y)(Iu - Cr) \\ & + y(1-x)(aRm - Cr) - (1-x)(1-y)Cr \end{aligned} \tag{11}$$

$$E_{n2} = xy(Rs + Iu - Cs) + y(1-x)(Rs - Cs) \tag{12}$$

$$E_n = yE_{n1} + (1-y)E_{n2} \tag{13}$$

According to Equations 11–13, the dynamic replication equation of scientific research institutes is denoted as $F(z)$.

$$\begin{aligned} F(z) &= \frac{dz}{dt} = z(En1 - En) \\ &= z(z-1)(Cr - Csy - Iux + Rsy - aRmy + Iuxy) \end{aligned} \tag{14}$$

Let's set it equal to 0: $z = 0, z = 1, x = \frac{Cr-y(Cs-Rs+aRm)}{Iu(1-y)}$

Taking the first derivative leads to the following:

$$\frac{dF(z)}{dz} = (2x-1)(Cr - Csy - Iux + Rsy - aRmy + Iuxy) \tag{15}$$

According to the stability theorem of a differential equation, the probability of a positive attitude in a scientific research institute in a stable state must meet the following requirements: $F(z) = 0$ 且 $\frac{dF(z)}{dz} < 0$. We can get the following proposition.

Proposition 3

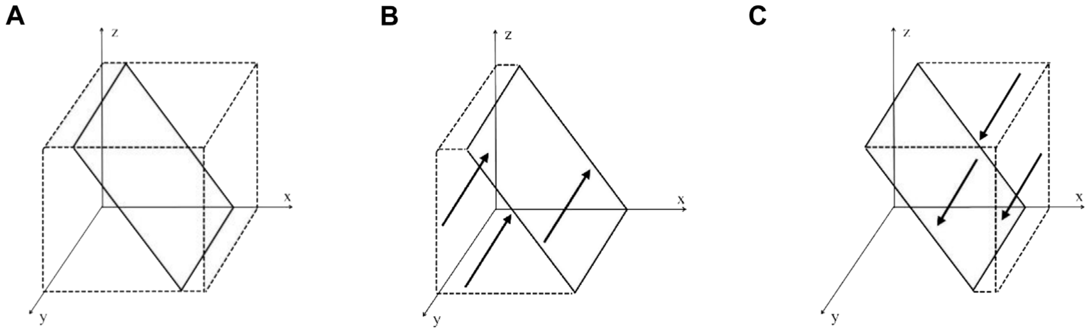

FIGURE 3
Dynamic evolution phase diagrams of SM building material manufacturers.

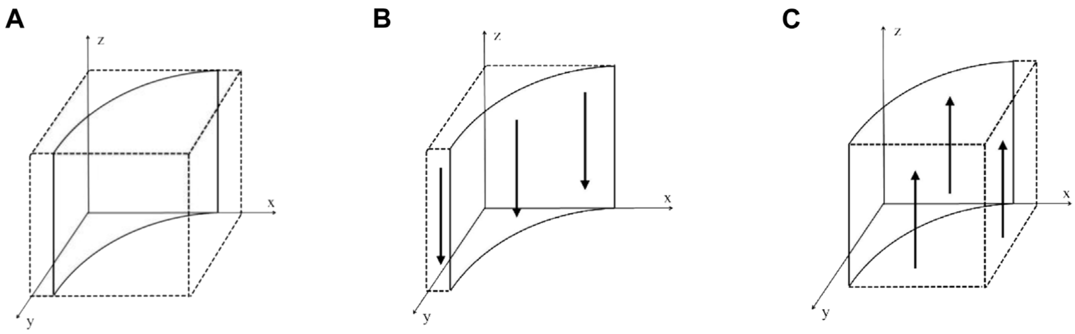

FIGURE 4
Dynamic evolution phase diagrams of research institutes.

1) If $x = x^* = \frac{Cr-y(Cs-Rs+aRm)}{Iu(1-y)}$ (Figure 4A, then $F(z) \equiv 0$. This means that no matter what takes any value (any attitude), the game is stable, and the research institute will get the same payoff.
2) If $x < \frac{Cr-y(Cs-Rs+aRm)}{Iu(1-y)}$ (Figure 4B), then $\frac{dF(z)}{dz}\Big|_{x=0} < 0$, In this case, $z = 0$ is the steady state, and the research institutes tend to be a partial attitude.
3) If $x > \frac{Cr-y(Cs-Rs+aRm)}{Iu(1-y)}$ (Figure 4C), then $\frac{dF(z)}{dz}\Big|_{x=0} > 0$, In this case, $z = 1$ is the steady state, and the research institutes tend to be a positive attitude.

3.3 Analysis of the game trend of evolutionary game theory

In conclusion, the Jacobian matrix J is used to analyze the ESS of the differential equation system. According to the dynamic replication equation of the above Equations 4 and 9 and (14), the Jacobian matrix J can be obtained as shown in Equation 16.

$$J = \begin{pmatrix} J_{11} & J_{12} & J_{13} \\ J_{21} & J_{22} & J_{23} \\ J_{31} & J_{32} & J_{33} \end{pmatrix} = \begin{pmatrix} \partial F(x)/\partial x & \partial F(x)/\partial y & \partial F(x)/\partial z \\ \partial F(y)/\partial x & \partial F(y)/\partial y & \partial F(y)/\partial z \\ \partial F(z)/\partial x & \partial F(z)/\partial y & \partial F(z)/\partial z \end{pmatrix} \quad (16)$$

$$\begin{aligned}
\partial F(x)/\partial x &= x^*(Cp - Cq - D - Rp + Rq + D^*y + Ie^*y + Iu^*y \\
&\quad + Iu^*z - Iu^*y^*z) \\
&\quad + (x-1)^*(Cp - Cq - D - Rp + Rq + D^*y \\
&\quad + Ie^*y + Iu^*y + Iu^*z - Iu^*y^*z) \\
\partial F(x)/\partial y &= x^*(x-1)^*(D + Ie + Iu - Iu^*z) \\
\partial F(x)/\partial z &= x^*(Iu - Iu^*y)^*(x-1) \\
\partial F(y)/\partial x &= -y^*(D + Ie)^*(y-1) \\
\partial F(y)/\partial y &= -(y-1)^*(Cn - Cm + Rm - Rn - Rs + D^*x + Ie^*x \\
&\quad + Rs^*z - a^*Rm^*z) \\
&\quad - y^*(Cn - Cm + Rm - Rn - Rs + D^*x + Ie^*x \\
&\quad + Rs^*z - a^*Rm^*z) \\
\partial F(y)/\partial z &= -y^*(Rs - a^*Rm)^*(y-1) \\
\partial F(z)/\partial x &= -z^*(Iu - Iu^*y)^*(z-1) \\
\partial F(z)/\partial y &= -z^*(z-1)^*(Cs - Rs + a^*Rm - Iu^*x) \\
\partial F(z)/\partial z &= (z-1)^*(Cr - Cs^*y - Iu^*x + Rs^*y - a^*Rm^*y + Iu^*x^*y) \\
&\quad + z^*(Cr - Cs^*y - Iu^*x + Rs^*y - a^*Rm^*y + Iu^*x^*y)
\end{aligned}$$

Let $F(x) = 0$、 $F(y) = 0$、 $F(z) = 0$ give us 14 equilibrium solutions. According to Friedman's evolutionary game theory, if the evolutionarily stable strategy satisfies the pure strategy Nash equilibrium, we can obtain the regular point of the evolutionary

TABLE 3 Eigenvalues of Jacobian matrix at eight equilibrium points.

Equilibrium points	λ_1	λ_2	λ_3
E1 (0,0,0)	$-Cr$	$Cq - Cp + D + Rp - Rq$	$Cn - Cm + Rm - Rn - Rs$
E2 (1,0,0)	$Iu - Cr$	$Cp - Cq - D - Rp + Rq$	$Cn - Cm + D + Ie + Rm - Rn - Rs$
E3 (0,1,0)	$Cs - Cr - Rs + a^{*}Rm$	$Cm - Cn - Rm + Rn + Rs$	$Cq - Cp - Ie - Iu + Rp - Rq$
E4 (0,0,1)	Cr	$Cn - Cm + Rm - Rn - a^{*}Rm$	$Cq - Cp + D - Iu + Rp - Rq$
E5 (1,1,0)	$Cs - Cr - Rs + a^{*}Rm$	$Cp - Cq + Ie + Iu - Rp + Rq$	$Cm - Cn - D - Ie - Rm + Rn + Rs$
E6 (1,0,1)	$Cr - Iu$	$Cp - Cq - D + Iu - Rp + Rq$	$Cn - Cm + D + Ie + Rm - Rn - a^{*}Rm$
E7 (0,1,1)	$Cr - Cs + Rs - a^{*}Rm$	$Cm - Cn - Rm + Rn + a^{*}Rm$	$Cq - Cp - Ie - Iu + Rp - Rq$
E8 (1,1,1)	$Cr - Cs + Rs - a^{*}Rm$	$Cp - Cq + Ie + Iu - Rp + Rq$	$Cm - Cn - D - Ie - Rm + Rn + a^{*}Rm$

system. Therefore, the following analysis highlights E1 through E8 in Table 3, which are equilibrium points, and all equilibrium points except these eight are not pure strategies but mixed strategies.

According to modern control theory, the equilibrium point is asymptotically stable when all λ_i $(i = 1.2.3)$ are negative. Since λ_1 is an obviously positive number in E4 (0,0,1), only the following seven cases need to be discussed.

According to the industry development theory, the stability and evolution process of SM building material manufacturers should be considered from the perspective of ILC. The industry life cycle is defined as the process from emergence to complete withdrawal from social and economic activities. Including initial period, rapid growth, steady development, and maturity (Cucculelli and Peruzzi, 2020). This study aims to divide ILC in the LBM industry into four stages.

Stage I: Initial phase. At this stage, SM building material manufacturers and scientific research institutes, LBM's R&D and production costs are higher than the profits, and the policy intensity is low. The government has realized that it should play its leading role and adopt a series of incentive and punishment policies to promote the development of the LBM industry. Specifically, the net utility of the government when implementing relative policies is greater than the net utility of implementing relative policies (i.e. $Rq - Cq < Rp - Cp + D$). The net utility of SM building material manufacturers in the production of LBM is less than the net utility of HBM under the carbon tax penalty (i.e. $Rm - Cm + Ie - Rs < Rn - Cn - D$). The net benefit of partial participation of research institutes in technology transfer is more significant than the government's subsidy (i.e. $Iu < Cr$). In summary, the optimal equilibrium point is E2 (1,0,0).

Stage II: Rapid growth. At this stage, due to the government's vigorous publicity and the application of incentive policies, SM building material manufacturers began to produce LBM actively. Specifically, the net utility of the government's relative policies is less than the benefits of the government's absolute policies minus costs and subsidies (i.e. $Rq - Cq < Rp - Cp - Ie - Iu$). Under the absolute government policy, the net utility of SM building materials manufacturers producing HBM is less than the net utility of producing LBM under the subsidy incentive (i.e. $Rn - Cn - D < Rm - Cm + Ie - Rs$). The net utility after using the income distribution coefficient under the positive attitude of scientific research institutes is less than the net utility of technology transfer under the attitude of the executive part (i.e. $aRm - Cr < Rs - Cs$). In summary, the optimal equilibrium point is E5 (1,1,0).

Stage III: Steady development. At this stage, as the production of LBM by SM building material manufacturers has grown and begun to take shape, scientific research institutes also actively pursue more excellent benefits. In particular, the government reaped considerable benefits from promoting low-carbon behavior (i.e. $Rq - Cq < Rp - Cp - Ie - Iu$). SM manufacturers will receive excess returns from the market and the government, enabling them to develop low-carbon behaviors (i.e.) vigorously. In addition, research institutes eventually realized that the additional benefits of positive attitude collaboration outweighed the different costs and decided to actively participate in the innovation of low-carbon technologies (i.e. $Rs - Cs < aRm - Cr$). Therefore, the government, SM building material manufacturers, and scientific research institutes are the leading players in the mature LBM industry. In summary, the optimal equilibrium point is E8 (1,1,1).

Stage IV: Mature phase. At this stage, the LBM industry has developed economies of scale. The government has been able to retreat from its dominant position. Specifically, under the premise that the government's absolute policy provides subsidy incentives, the benefits of the government's implementation of absolute policy minus costs and subsidies are smaller than the net utility of the government's implementation of relative policies (i.e. $Rp - Cp - Iu - Ie < Rq - Cq$). Under the relative policies of the government and the positive attitude of scientific research institutes, the net utility of SM building material manufacturers in producing LBM is greater than that in producing HBM (i.e. $Rn - Cn < (1 - a)Rm - Cm$). The net utility of the research institute implementing partial attitude is less than the net utility of the revenue minus the cost after the distribution coefficient of the contract system under the positive attitude (i.e. $Rs - Cs < \alpha Rm - Cr$). In summary, the optimal equilibrium point is E7 (0,1,1).

4 Numerical simulation

In this section, we use MATLAB R2016a to conduct numerical simulation experiments. Considering that many variables and parameters are involved, and the relationship between them is complex, it is not easy to measure in actual cases, so this study does not set values according to specific topics. The initial parameters were assessed through a questionnaire survey, inquiry of industry experts, and reference of previous papers published in similar research. On this basis, the initial value Settings are shown in Table 4.

TABLE 4 Parameter values of each stage in the evolutionary game model.

Parameters	Stable point	D	a	Rn	Rm	Rp	Rq	Rs	Cn	Cm	Cp	Cq	Cr	Cs	Iu	Ie
Initial stage	(1,0,0)	5	0.3	15	15	50	25	8	5	8	10	6	10	3	5	5
Rapid development	(1,1,0)	5	0.3	15	40	50	25	10	5	8	10	6	10	3	5	5
Steady development	(1,1,1)	3	0.3	15	40	50	25	8	5	8	10	6	5	3	5	5
Mature phase	(0,1,1)	5	0.3	15	40	25	25	8	5	8	10	6	5	3	5	5

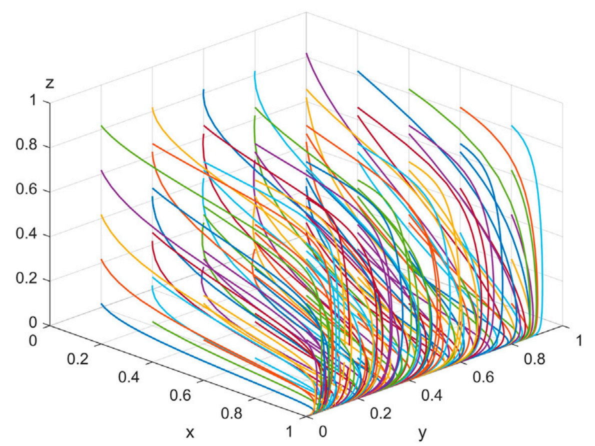

FIGURE 5
System evolution in the initial stage.

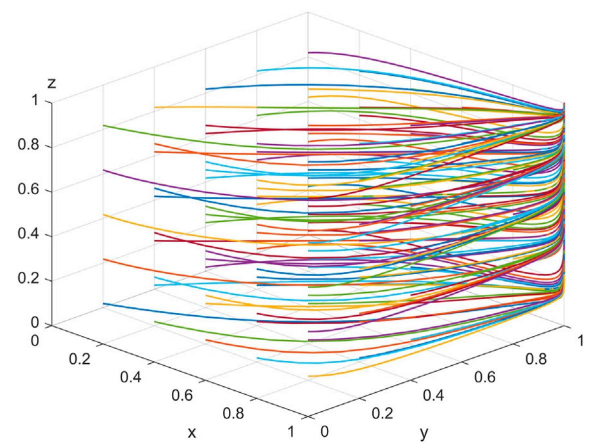

FIGURE 7
System evolution process in the steady development stage.

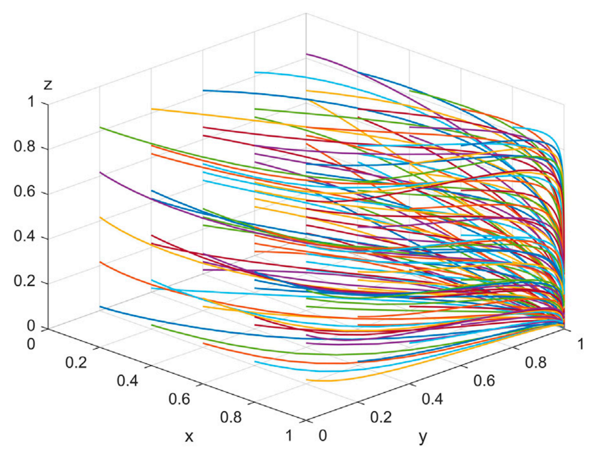

FIGURE 6
System evolution process in the rapid development stage.

4.1 Multi-stage dynamic evolution results

4.1.1 Dynamic evolution of stakeholders in the initial stage

Following the stability conditions calculated above in the initial phase (i.e. $Iu < Cr$; $Rm - Cm + Ie - Rs < Rn - Cn - D$), A value is assigned to each parameter of the numerical simulation. MATLAB 2016a simulated 50 different initial value strategy combinations of three stakeholders. Figure 5 shows the evolution trend of the three-way evolutionary game with lines of different colors, which eventually converge to E2 (1, 0, 0). This dynamic evolution simulation diagram proves that E2 (1, 0, 0) is the ESS in the system when the constraints are consistent with the initial phase. Specifically, the government decided to undertake high financial pressure to promote the development of LBM. The unclear benefits have led SM building material manufacturers to continue producing HBM. In addition, due to the lack of a complete LBM project and uncertain market prospects, research institutes are still more reluctant to cooperate actively.

4.1.2 Dynamic evolution of stakeholders in the rapid development stage

Similarly, the simulation is performed using stability conditions (i.e. $Rq - Cq < Rp - Cp - Ie - Iu$; $aRm - Cr < Rs - Cs$), as shown in Figure 6. All these lines eventually converge to E5 (1,1,0), which is confirmed as the ESS of the evolution model at this stage. Specifically, the government has become more convinced of the benefits of advocating and promoting low-carbon industries, further stimulating the market. At the same time, SM building material manufacturers are starting to follow this trend as they believe that the actual profit from producing LBM can reach the expected target with subsidies and are confident about the future market size. However, due to the limited knowledge of LBM technology, research institutes still maintain the strategy of partial attitude.

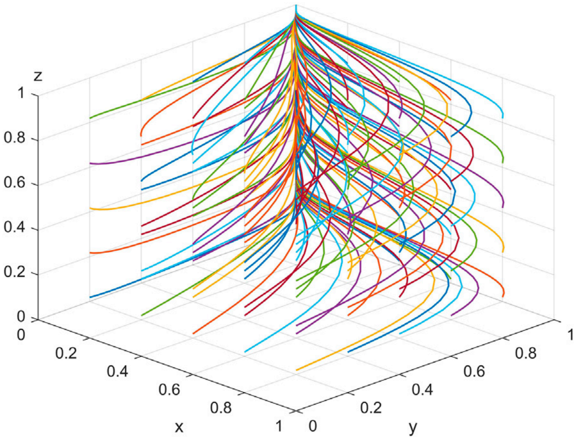

FIGURE 8
System evolution process at a mature stage.

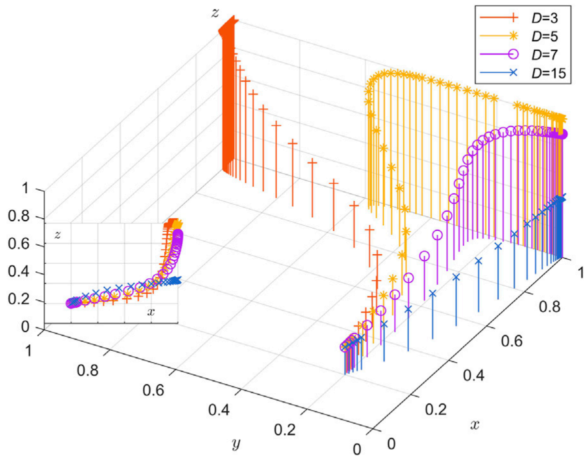

FIGURE 9
Impact of a carbon tax D on stakeholder behavior evolution.

4.1.3 The dynamic evolution of stakeholders in the stable development stage

According to the stable development stage shown in Table 4, the corresponding stability conditions of each parameter value include $(Rq - Cq < Rp - Cp - Ie - Iu;\ Rs - Cs < aRm - Cr)$. as shown in Figure 7. After similar simulations, it can be observed that after several iterations, the lines converge to the equilibrium point of E8 (1,1,1), which also determines the ESS of the rapid development phase. In this regard, inspired by R&D and material cost reduction, SM building material manufacturers are more committed to producing LBM to maintain economic efficiency under government subsidies. In addition, the behavioral strategies of research institutes gradually shifted to a positive attitude as they identified the prospective value of LBM.

4.1.4 The dynamic evolution of stakeholders in the mature stage

Based on the stability conditions at maturity (i.e. $Rs - Cs < \alpha Rm - Cr;\ Rp - Cp - Iu - Ie < Rq - Cq$). As shown in Figure 8,.which is verified to be the asymptotic stable point of the evolving system. In fact, with the significant progress of the low-carbon industry under government regulation, on the one hand, for the sake of enhancing social responsibility and stabilizing comprehensive benefits, SM building material manufacturers have accepted the industry trend of developing LBM. On the other hand, research institutes have recognized the advantages of active participation in LBM, considering the growing market size and supply chain and the environmentally friendly societal position. In this way, the LBM industry will shift from government regulation to market autonomy, and the government can gradually detach from the market and stimulate its independent development.

4.2 Impact of a carbon tax on the path

The carbon tax D is set to 3, 5, 7, and 15, respectively, as shown in Figure 9, when $D = 3$, y gradually decreases to 0, and when $D = 7$ and $D = 15$, z gradually moves away from one and approaches 0. This indicates that both low and excessive carbon tax penalties are not conducive to improving the willingness of SM building materials manufacturers and scientific research institutes to choose low-carbon innovation. However, y and z stabilize at one only when $D = 5$, indicating that an appropriate carbon tax penalty can change the attitudinal strategies of SM building materials manufacturers and research institutes towards LBM. Moreover, since carbon taxes can also enhance the government's returns, x is always stable at one to reflect the dominant position. In summary, the simulation results show that insufficient punishment is not guaranteed to promote the optimal evolution of the three-way strategy, while excessive punishment will have corresponding adverse effects. Only when the carbon tax penalty rises to a certain level will stakeholders adjust their behavioral strategies after comparing incremental costs and additional benefits and finally evolve to a stable state. In addition, research institutes are also negatively related to changes in government penalties. A plausible explanation is that institutions are at the end of the LBM technology supply chain and are, therefore, more concerned with the future value (such as price, advantage, and quality) that LBM presents than just accepting the market.

4.3 The size of government input cost under the absolute policy

The absolute policy cost to the government is a significant obstacle to monitoring the LBM industry. To this end, the simulation results are shown in Figure 10 for four values of Cp (namely $Cp = 5; Cp = 10;$ $Cp = 20;\ Cp = 22$). When $Cp = 5$, $Cp = 10$ and $Cp = 20$, $x = 1$ is always present, but with the increase of Cp, the evolution tends to $x = 0$. Thus, it is revealed that the government's willingness to regulate LBM projects by absolute policy decreases with the rise Cp. It is found that there is an interdependent relationship between the government and research institutes. In the early stage, the sensitivity of research institutes to cost is similar to that of the government. However, when the government input cost increases, research institutes can obtain more social and economic benefits, and the sensitivity will significantly improve. However, when $Cp = 22$, the government's behavior strategy shifts to the relative attitude. As continuous development leads to a

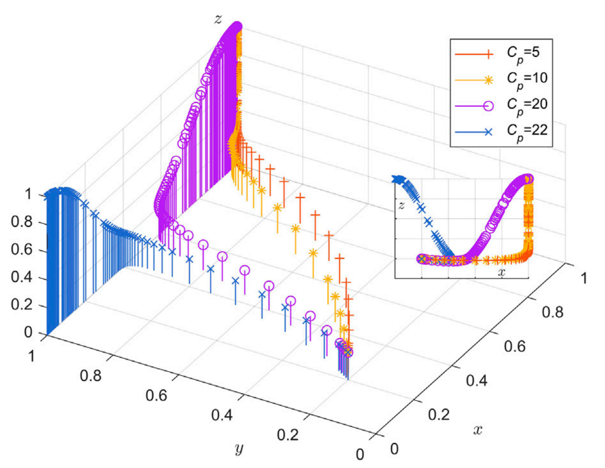

FIGURE 10
Impact of cost *Cp* on stakeholder behavior evolution.

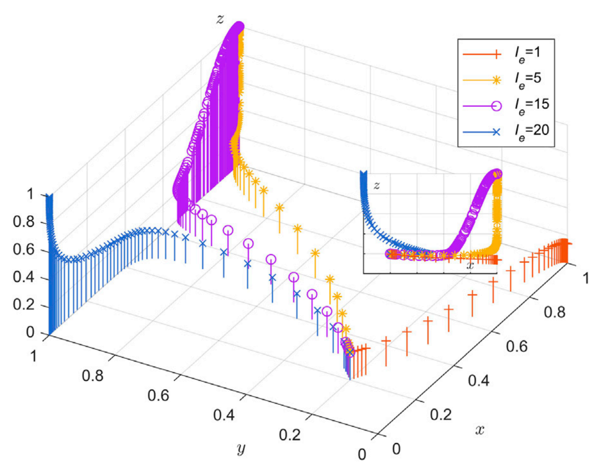

FIGURE 11
The influence of subsidized *Ie* on the evolution of stakeholder behavior.

larger and larger scale, the absolute attitude of regulation will consume much workforce and material resources, resulting in the government slowly relaxing limitations into a relative attitude.

4.4 Green subsidies for SM building material manufacturers under the absolute attitude of the government

See Figure 11. Numerical simulations were performed for $Ie = 1$, $Ie = 5$, $Ie = 15$, and $Ie = 20$. The results show that $y = 0$ and $z = 0$ when $Ie = 1$.SM building material manufacturers and scientific research institutes tend not to participate in developing the LBM industry. The research shows that when the subsidy is relatively low, the two parties show a negative attitude toward the market uncertainty and the shortage of funds. With the continuous increase of green subsidies ($Ie = 5$; $Ie = 15$), both sides will tend to participate in developing the LBM industry, but there are specific differences in the sensitivity of participation. If the green subsidy is too small, both parties cannot fully bear the production cost and R&D cost of LBM. Therefore, once the intensity factor of green subsidies reaches a certain threshold, the decisions of SM building materials manufacturers and scientific research institutes will eventually be added to the LBM industry strategy. However, when $Ie = 20$, the government changes from absolute policy to relative policy due to high green subsidy expenditure. It can be seen that the construction of a reasonable green subsidy system is necessary for developing the LBM industry.

4.5 Revenue from selling technology of research institutes under relative attitude

Part of the attitude of research institutes to sell *Rs* is the main obstacle to developing the LBM industry. To do this, see Figure 12. Numerical simulations were performed for $Rs = 8$, $Rs = 15$, $Rs = 25$, and $Rs = 40$. The results show that when $Rs = 8$ is adjusted to $Rs = 15$ and $Rs = 25$, z finally drops to 0. It is found that with the increase of *Rs*, scientific research institutes no longer actively cooperate with SM building materials manufacturers but transfer technology in the form of sales. The higher the price, the more inclined the SM building materials manufacturers are to produce HBM. There is an interdependence between the dominant strategies of SM building materials manufacturers and the attitudes of research institutes, especially when the high premium for producing LBM cannot offset its additional costs. Research institutions are often slow to react to changes in the market, which could weaken the knock-on effect between the two sides. When $Rs = 40$, both y and z eventually drop to 0, the behavior strategies of SM building materials manufacturers and scientific research institutes turn to HBM production and partial attitude, respectively. Therefore, in addition to policy regulation, the government should pay more attention to the regulation of technology transfer and sale prices in the market so as to reduce R&D costs and material costs, so that the strategic choice of the tripartite system can evolve into a stable state of LBM promotion.

4.6 Size of distribution coefficient

We set a as 0.1, 0.3, 0.5, and 0.7, respectively, to conduct a numerical simulation of the three-party game model, and the results are shown in Figure 13. When $a = 0$, z is stable at 0, which indicates that because the benefits obtained by research institutes may not be accepted, the expected returns will hinder the initial enthusiasm of research institutes to develop LBM technology. However, when $a = 0.3$ and $a = 0.5$, the research institute obtains the expected return, the stable strategy will eventually evolve into active cooperation. When $a = 0.7$, due to excessive benefits flowing into scientific research institutes, SM building materials manufacturers will no longer insist on producing LBM. The allocation coefficient a is introduced to improve the enthusiasm of technology R&D personnel from the perspective of ILC, not only the R&D of low-carbon technologies. Specifically, due to potential skepticism about the LBM primary market by research institutes, higher unknowns may hinder research institutes from developing technologies to produce LBM.

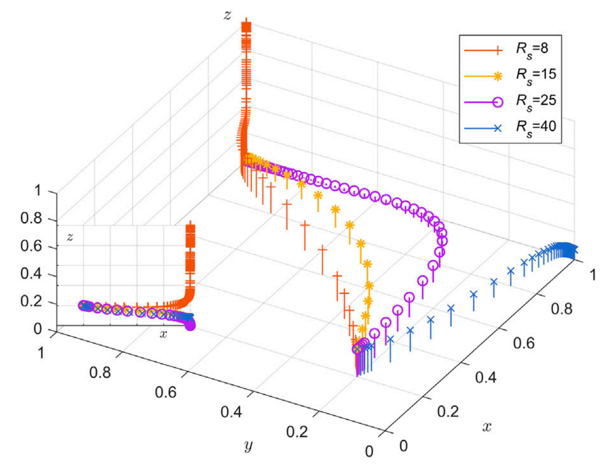

FIGURE 12
The impact of revenue *Rs* on the evolution of stakeholder behavior.

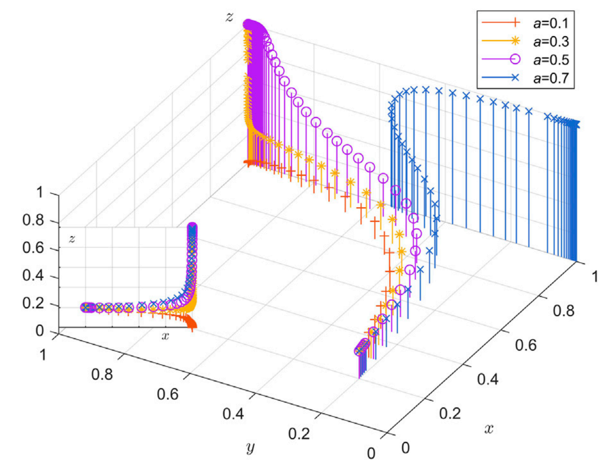

FIGURE 13
Influence of coefficient *a* on the evolution of stakeholder behavior.

Therefore, it is crucial to formulate a reasonable income distribution coefficient *a* to sustain the long-term development of production LBM without putting severe pressure on SM building materials manufacturers.

5 Discussion and policy recommendations

5.1 Low-carbon building materials industry promotion mechanism

In the initial stage, the LBM industry is in its infancy, and the market is full of unknowns in terms of capital and technology. At this time, the government should play a leading role. The immaturity of the technology and the shortage of capital lead to higher costs, which largely hinder the development intention of SM building materials manufacturers. Firstly, the government should vigorously promote the advantages of green and low-carbon and raise the low-carbon awareness of manufacturers, therefore, the government can introduce a series of subsidies, guidance policies, and other incentive measures. Secondly, the government should develop punitive measures by introducing carbon emission taxes and environmental pollution fines for those SM building materials manufacturers who still produce HBM. Since research institutes do not see the prospective market for LBM. In this regard, the future development of the LBM market should be promoted through effective government.

In the stage of rapid and steady development, SM building materials manufacturers, with the assistance of government and research institutes, become the main body leading the whole market. Firstly, in order to reduce the investment of government regulation costs, the government should change to a relative attitude. Secondly, continue to stimulate and guide SM building materials manufacturers and research institutes to actively cooperate and join the LBM industry. Encourage the transformation from the original supply chain model of purchasing technology to the green service model of signing contracts between the two parties, and link the benefits of both through the revenue allocation coefficient to motivate research institutes to optimize their technology and avoid opportunistic behavior.

In the mature stage, the LBM industry has developed according to certain economic laws, and both sides of the cooperation have clarified their respective costs and benefits. At this stage, it is more important to focus on the institutional aspect, especially the market-oriented rules, standards, and even laws for LBM should be further established and improved. The previous incentive of allowance should be gradually changed to the institutional incentive to reduce the dependence of the LBM industry on the government. Secondly, guiding the establishment of public supervision behavior to regulate the development behavior of both sides of the cooperation is more helpful to the future development of the industry.

5.2 Policy recommendations

1) The government gives subsidy incentives and carbon tax penalties

At the early stage of industry development, fully motivate SM building materials manufacturers and research institutes to participate in LBM, so that the development of LBM becomes a carbon reduction project with the participation of multiple entities. However, we should adhere to the principle of moderation of subsidies and carbon tax penalties, and the amount is not the more the better. The amount of subsidy is too low and cannot play an incentive role for enterprises and research institutes, while the amount is too high will disturb the stability of the market price system and lead to unfair social distribution.

2) The government establishes a sound market development mechanism

The government establishes a reasonable and healthy market development mechanism to attract more SMEs to join it. Gradually change from allowance incentives to system incentives to reduce the dependence of the LBM industry on the government and promote the high-quality and independent rapid development of the LBM industry.

3) Establishment of a social monitoring system by the government

For research institutes to supervise their performance in developing LBM technologies through credit upgrades and downgrades related to their brand value and social image in the research community can help reduce the cost of government oversight. The formation of an autonomous LBM market dominated by SM building materials manufacturers through social oversight, as well as the establishment of public oversight to regulate the development behavior of both partners is more conducive to the future development of the LBM industry.

6 Conclusion

Using green technology to produce LBM is one of the effective ways to control carbon emissions and achieve carbon neutrality. This paper not only considers the limitations of SM building material manufacturers under the constraint of the carbon tax but also considers four stages of LBM production: initial period, rapid growth, steady development, and maturity, and realizes the industry life cycle analysis of LBM, which is more comprehensive than previous studies. Based on the simulation analysis results, the following conclusions are obtained.

This paper considers the industry life cycle process. It obtains: 1) in the initial stage, under the premise of high uncertainty of the market prospect, the government is dominant. Implementing appropriate subsidy incentives and carbon tax penalties under high financial pressure can promote the low-carbon transformation of the other two sides. 2) In the stage of rapid development and stable development, combined with the path evolution slope of Rs and a, the income distribution coefficient a under the contract system can be used to link the benefits of the two, which can stimulate the enthusiasm of scientific research institutes to optimize technology and avoid “free riding” behavior. 3) In the mature stage, the LBM industry will shift from regulated to autonomous, and the government can gradually detach from the market to stimulate its independent development. Secondly, establish the public supervision behavior, reputation status, and so on to regulate the development behavior of both.

This study discusses the influence of some critical parameters through numerical simulation. The results show that: 1) Lower and higher carbon taxes penalty is not conducive to improving the willingness of SM building material manufacturers and scientific research institutes to choose the low-carbon industry. An appropriate carbon tax penalty can accelerate the production of LBM to a stable state. 2) There is an interdependent relationship between the government and research institutes. In the early stage, the sensitivity of research institutes to cost is similar to that of the government. However, as the government input cost continues to increase, research institutes are full of confidence in the LBM market. They can obtain more social and economic benefits so that the sensitivity will be significantly improved. 3) The subsidy amount of the LBM industry is not the more, the better. The subsidy amount is too low to stimulate enterprises and research institutes, while the subsidy amount is too high to disturb the stability of the market price system, resulting in social distribution injustice. 4) Combined with the path evolution slope of Rs and a, it can be obtained, and the benefits of the two are linked by the benefit distribution coefficient a, which can stimulate the enthusiasm of scientific research institutes to optimize technology and avoid “free riding” behavior.

Although the paper has contributed to the theoretical research, it has some limitations: for data acquisition, there are problems such as time limit and objective reality. The real market situation is much more complex than the simulated game model, and this study is limited to abstracting the three primary agents in LBM production to simplify the model. In contrast, more agents and variables may need to be considered in the real market. Therefore, it is necessary to carry out further numerical simulation research on this aspect.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

QX and YL: Conceptualization, first draft writing, and approach are handled. CC: oversight and formal evaluation. Variable construction, FL: Data management.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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