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# Steady-state analysis of social responsibility strategy of coal power enterprises from the perspective of game theory

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ABSTRACT

Under the dual-carbon background, coal power enterprises are required to actively fulfill their social responsibility in order to achieve energy saving and emission reduction as soon as possible. Considering the uncertainty of the external environment and the potential conflict of interest of the key stakeholders in the fulfillment of corporate social responsibility, coal power enterprises are not always positive in fulfilling their social responsibility. This paper combines prospect theory and mental account theory with evolutionary game to construct an evolutionary game model involving coal power enterprises, government regulators and the public to study the social responsibility behavior of coal power enterprises. The results of the study show that: (1) The social responsibility behavior of coal power enterprises under the dual-carbon background is a typical cost-driven behavior, and coal power enterprises are more sensitive to costs compared to benefits. (2) The formulation of regulatory policies by government regulators largely depends on the decision inertia of coal power enterprises, and the formulation of regulatory policies by government regulators will also affect the decision inertia of coal power enterprises. (3) The public's strategic choices do not entirely depend on the strategic choices of coal and power enterprises and government regulators, and are more closely related to the setting of the reference point. (4) In addition to the realistic factors, the subjective factors of decision makers are also important factors affecting the fulfillment of social responsibility of coal and power enterprises. Based on the results of the study, this paper proposes countermeasures to enhance the internal driving force of coal power enterprises to fulfill their social responsibility behaviors from the aspects of establishing a communication mechanism, improving the reward and punishment system, and strengthening risk management.

## 1. Introduction

### *1.1. Background*

With the increasing prominence of environmental problems [1], countries have been or are facing serious environmental crises [2]. The current environmental situation has pushed countries around the world to actively cooperate and put forward various energy-saving and emission-reduction measures one after another [3]. Double carbon is a two-stage carbon emission reduction goal

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put forward by China (referred to as “double carbon" strategic goal), which means that carbon dioxide emissions will peak in 2030 and be carbon neutral in 2060.

In this context, energy transformation is precisely a key initiative to promote the realization of the goal [4,5]. In the path of energy transformation, coal enterprises and electric power enterprises are two important obstacles to reduce pollutant emissions, joining the “coal abandonment alliance"(reduce the utilization and consumption of coal), coal power plant decommissioning (elimination of outdated coal power production capacity) and other initiatives have gradually become a general trend [6,7]. However, under the concept of green development, coal and oil control policies have been frequently introduced, but the “cold" thinking in the “hot" environment is more conducive to the smooth promotion of the “transition" of China’s institutional structure transformation [8]. Considering China’s “coal-rich, oil-poor, gas-poor" energy status quo [9], as well as other energy generation needs to be clarified the economic feasibility and security of power supply of the strong uncertainty [10], to guide and constrain the coal power enterprises to resource integration [11], “coal reduction" accompanied by clean utilization of energy should be the path dependence of China.

Coal is a kind of high pollution, high emission non-clean energy [12], and China’s power structure is mainly dominated by traditional thermal power generation [13], in the process of coal power generation inevitably produces a large number of pollutants or wastes, coal enterprises and power enterprises as an important carrier to improve the current situation, the fulfillment of social responsibility is its obligatory mission. Corporate Social Responsibility (CSR) is a broad concept. For electric power enterprises, it is necessary to ensure a stable supply of electricity and affordable electricity prices for residents while taking into account the environmental benefits and reducing carbon emissions [14]; for coal enterprises, in addition to the most basic responsibilities to stakeholders, more emphasis is placed on achieving ecological and environmental protection and improving resource utilization [15] from clean utilization and green mining [16]. At the same time, people’s concern for physical and mental health and the protection of their own rights and interests has led to increasing public opinion pressure, and it has become an urgent issue for coal and power enterprises to actively assume social responsibility.

Although active fulfillment of social responsibility by coal power enterprises can help improve their corporate image and can effectively enhance their competitiveness [17], and consumers with low carbon preference are willing to pay higher prices when purchasing low carbon products [18], the high initial investment and operation and maintenance costs of environmental protection facilities put coal power enterprises in a dilemma [19]. For a long time, China’s factor markets, especially energy factor markets, have been subject to government regulation and market segmentation [20], and market-oriented reforms have lagged behind. In the existing practice, the government mainly requires coal power plants to carry out energy saving and emission reduction by means of huge fines or even mandatory closure, and such mandatory measures not only suppress the endogenous social responsibility behavior of enterprises [21], but also easily lead to the conflict of interest among government regulators, coal power enterprises and the public.

Based on the status quo of social responsibility fulfillment of coal power enterprises and the conflict of interests among multiple subjects in the dual-carbon background, we constructed a tripartite evolutionary game model with the joint participation of government regulators, coal power enterprises and the public, and specifically, we aim to address the following research questions.

(1) What are the characteristics of the fulfillment of social responsibility behaviors of coal power enterprises in the dual-carbon context? When do coal power enterprises actively fulfill their social responsibility? When will they negatively fulfill their social responsibility?
(2) In the face of the conflict between energy supply guarantee and emission reduction goals, how should government regulators formulate regulatory policies?
(3) What is the role of the public in this process? How does the public’s attitude affect the social responsibility behavior of coal power enterprises?
(4) If coal power enterprises have risky attitudes and decision-making preferences, how do risk aversion and subjective preferences in decision-making affect the social responsibility practices of coal power enterprises?

### *1.2. Contribution statements*

This study has two main innovations and potential contributions.

(1) Based on the endogenous social responsibility behavior of coal power enterprises, it explores how to guide and constrain coal power enterprises to integrate resources in a “hot" environment with a “cold" mindset by portraying the complex game behavior of coal power enterprises, government regulators and the public. To clarify the endogenous path of coal power enterprises’ participation in energy conservation and emission reduction, and to analyze how the exogenous roles of government regulators and the public influence the social responsibility practices of coal power enterprises.
(2) Introduce prospect theory and psychological account theory into evolutionary game analysis, expand expected utility theory non-linearly, systematically analyze the influence of irrational factors such as risk preference and cost preference on the social responsibility practice of coal power enterprises, and put forward countermeasures and suggestions from the aspects of mechanism design and endogenous drive, so as to enrich the theoretical achievements and practical paths of social responsibility behavior of coal power enterprises.

### 1.3. Organization

The rest of the paper is organized as follows. We review the relevant literature in Section 2. In Section 3, we briefly introduce the theoretical foundation of the paper. In Section 4, we give the research framework of the paper and explain the construction of the three-party evolutionary game model step by step. In Section 5, we analyze the evolutionary game model in terms of strategy stability analysis and strategy combination stability analysis in turn. In Section 6, we use simulation software to simulate the game model and discuss the effects of key parameters on the model. Finally, we discuss the research conclusions and future research directions in Section 7.

## 2. Literature review

### 2.1. Coal power industry symbiosis

With the development of digital economy and the application of emerging information technology [22], the supply and demand structure of China coal market and electricity market is undergoing profound changes. In order to better promote the optimization and upgrading of the industrial structure, and to alleviate the conflict between "saleable coal" and "saleable electricity" [23,24], the symbiosis of coal and power industries has been highly valued by Chinese and local governments. Coal and power industry symbiosis refers to the joint development and production of coal and electricity, forming a vertically integrated structure [25], breaking down industry barriers through resource sharing and mutual support, and enhancing the complementarity and synergy between coal and power enterprises. Practice has proved that the symbiosis of coal and power industry can effectively enhance economic and environmental benefits, and better realize energy conservation, emission reduction and sustainable development [26].

### 2.2. Game theory

By drawing on biological evolution and its behavioral laws, Maynard proposed the idea of evolutionary games on the basis of classical game theory in 1973 [27]. Due to the applicability of evolutionary games in portraying the changing law of decision makers' behavior in multi-period and long-stage processes [28], it has been widely used in many fields, such as green transformation [29], adoption of new energy technologies [30], manufacturing transformation [31] and security inputs [32]. The fulfillment of socially responsible behavior is a long-term activity, and evolutionary games have been widely used in CSR-related research due to their ability to effectively portray the dynamic laws of behavior over time. Dang et al. [33] constructed an evolutionary game model to study the socially responsible behavior of construction firms. Johari et al. [34] analyzed the pricing and behavioral strategies of socially concerned manufacturers through evolutionary game theory. Sun et al. [11]constructed an evolutionary game model based on the perspective of government regulation, and discussed how to guide and constrain coal enterprises to carry out resource integration behavior, and whether the government supervised this behavior. Ma et al. [35] analyzed the evolution of manufacturers' and e-commerce retailers' behaviors under changes in government regulation by constructing an evolutionary game model. Although the above studies have taken into account the limited rationality of decision makers and are more in line with reality, they have not overcome the limitations of expected utility theory [36], nor have they considered the influence of psychological perception and risk preference on strategy selection of multiple subjects of CSR behaviors, so the credibility of their conclusions and the effectiveness of their explanations of the reality are worth further debating.

### 2.3. PT_MA theory

In order to be closer to the psychological activities and perceptions of decision-making subjects when facing gains and losses, and to portray the real human judgments and decision-making behaviors under uncertainty, Kahneman et al. [37] proposed the prospect theory, and Thaler also proposed the mental account theory based on the prospect theory, which is more reflective of the real decision-making behaviors of human beings [38]. Subsequently, the combination of this theory and evolutionary games has been widely used in the fields of Public Private Partnership project regulation [39], energy structure transformation [4], environmental regulation [40], and other fields, and more fruitful research results have been achieved.

In summary, prospect theory and mental account theory can be effectively integrated with the evolutionary game method, which can also reflect people's behavioral decisions more scientifically and realistically. However, few studies have used this theory to explore the behavioral decision-making of social responsibility of coal power enterprises. Based on the psychological account, this paper uses the prospect value function to construct the prospect benefit-payment value perception matrix to analyze the real decision-making behaviors of coal power enterprises, government regulators and the public in an evolutionary game, and to objectively verify the influence of each factor on the behavioral evolution path.

## 3. Theoretical assumption

### 3.1. Prospect theory

Prospect theory is a behavioral theory used to describe individuals' decision-making based on risk expectations and probabilities in situations of uncertain prospects. The theory is based on the assumption of finite rationality and finds that there are differences in people's risk preferences in the face of gains and losses, which are manifested in risk-seeking in the face of losses and risk-avoidance in the face of gains. Here, gains and losses are measured according to pre-set reference points, and reference point deviations affect decision makers' emotions, which in turn affect their behavior.

The prospect function expression is $V = T(\Delta\pi)w(\varepsilon)$. Where $V$ denotes the overall value perception of an individual, $T(\Delta\pi)$ is the value function, $w(\varepsilon)$ is the decision weight function, $\Delta\pi$ is the deviation of the actual value from the perceived value, and $\varepsilon$ denotes the probability.

### 3.2. Mental account theory based on prospect theory

Mental Account Theory is the tendency of people to divide their wealth into different accounts on a psychological level according to various subjective criteria. Based on this, the value function $T(\Delta\pi)$ is divided into the potency account $P(x)$ and the cost account $(x)$ , which is expressed as:

$$P(x) = \begin{cases} (x - U0)^{\beta}, x \geq U0 \\ -\lambda(U0 - x)^{\theta}, x < U0 \end{cases} C(x) = \begin{cases} \delta(x - U1)^{\upsilon}, x \geq U1 \\ -(U1 - x)^{\sigma}, x < U1 \end{cases}$$

Fig. 1(a) shows the functional diagram of the valuation account, $U0$ is the valuation reference point; Fig. 1(b) shows the functional diagram of the cost account, $U1$ is the cost reference point; and it is obvious that the psychological level of the decision maker changes at the reference point. $\lambda$, $\delta$ are the sensitivities of valuation and cost loss aversion, respectively; $\beta$, $\theta$ are the valuation risk preference coefficients; $\nu$, $\sigma$ are the cost risk preference coefficients. In addition, the decision weight function represents the subjective judgment

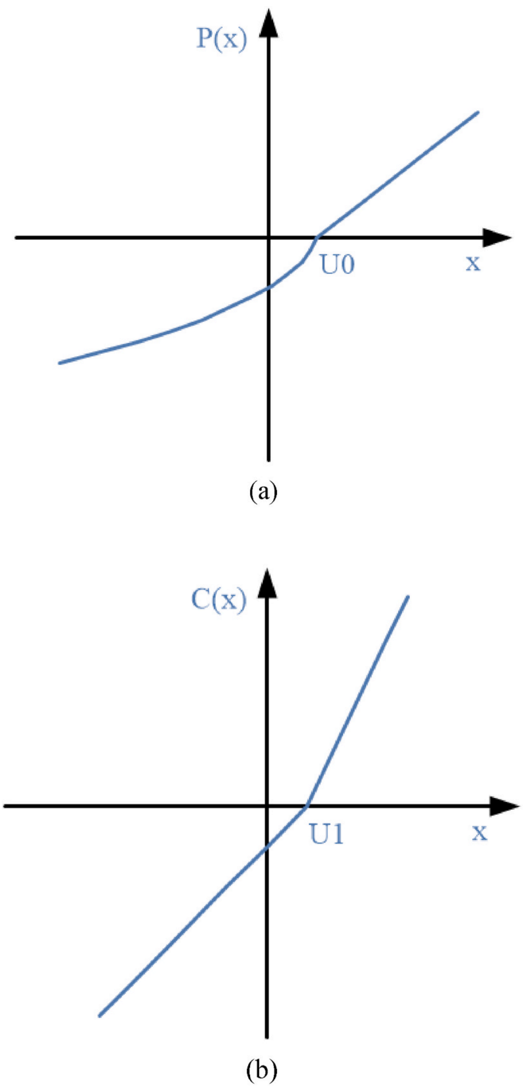



**Fig. 1.** Value function of PT-MA.

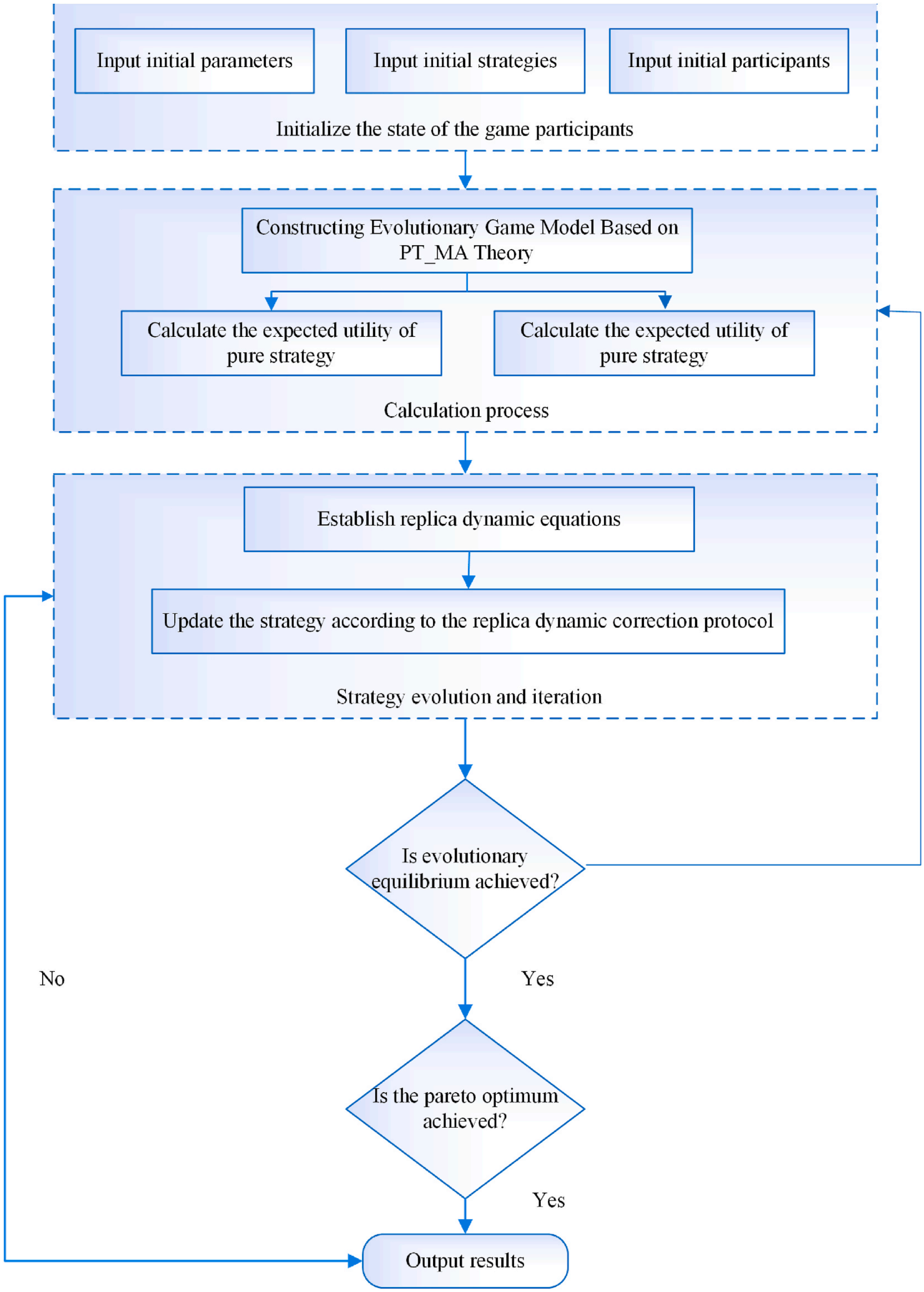



**Fig. 2.** Research frame diagram.

of the decision maker on the probability of the event or the tendency to choose the strategy, and its expression [41] is:

$$w(\varepsilon) = \frac{\varepsilon^{\iota}}{[\varepsilon^{\iota} + (1 \pm \varepsilon)^{\iota}]^{\frac{1}{\iota}}}$$

Where, $\iota$ is the decision influence coefficient.

### 3.3. Application of PT_MA theory

PT_MA theory is also very closely linked to the real world. For example, people are more emotionally volatile when they lose $100 than when they gain $100, which is consistent with the assumption in prospect theory that decision makers are more sensitive to losses. In addition, when shopping, a $5 discount on a $5000 item may seem insignificant, but it is a very large discount on a $10 item, because people judge what is happening based on the proportion of difference from the reference point, and changes in the reference point lead directly to people's utility perceptions.

## 4. Game modeling

### 4.1. Research framework

The introduction and theoretical assumption explain the key problems to be solved in this paper theoretically. In this chapter, we will make a nonlinear expansion of the evolutionary game model based on PT_MA theory, and discuss the evolutionary mechanism of social responsibility behavior of coal power enterprises based on numerical calculation and simulation analysis. The research framework of this paper is shown in Fig. 2.

### 4.2. Problem description

This study takes the starting point of the problem of how to take into account the social responsibility of coal and power enterprises while realizing economic benefits, and constructs a tripartite evolutionary game model with the participation of coal and power enterprises, government regulators and the public. The schematic diagram of the three-party evolutionary game is shown in Fig. 3.

The participants involved in the CSR fulfillment problem of coal and power enterprises are coal and power enterprises, government regulators and the public. Among them, the public is the disadvantaged group that is victimized when the enterprises perform CSR negatively; the enterprises in the coal and power supply chain are regarded as a whole mainly responsible for guaranteeing the CSR behaviors such as power supply, clean energy development, and environmental protection; the government regulator subsidizes or

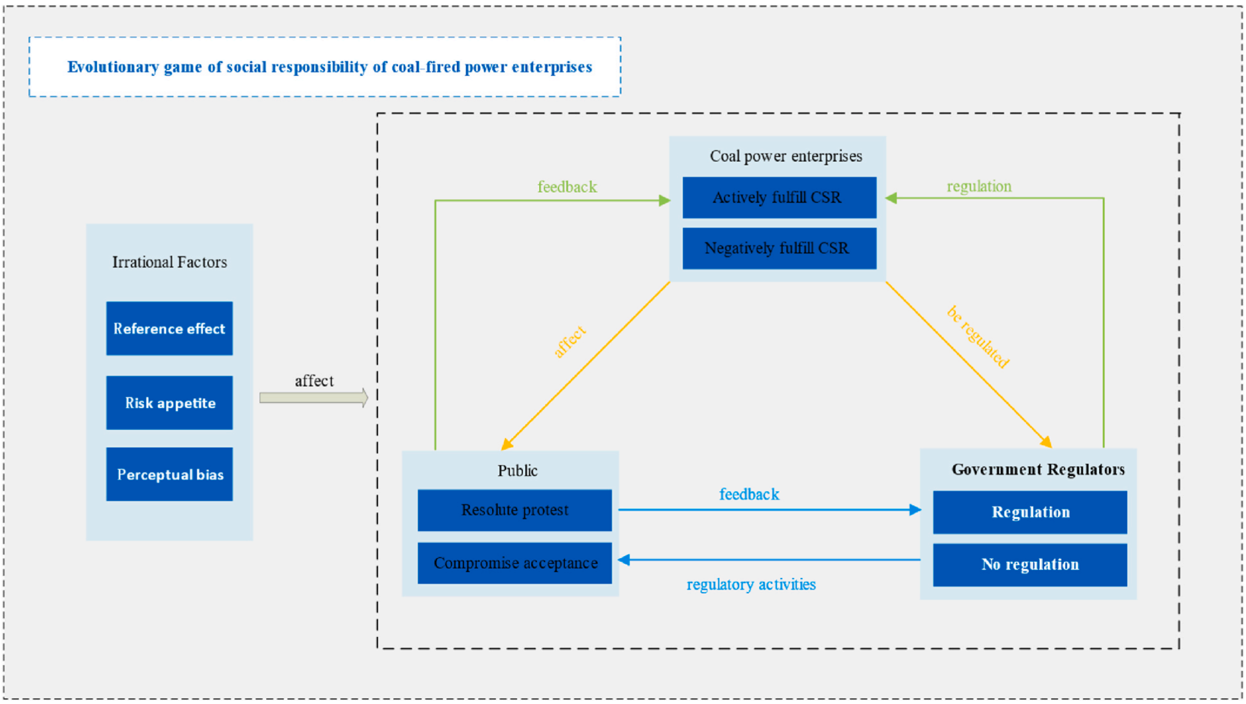



**Fig. 3.** Schematic diagram.

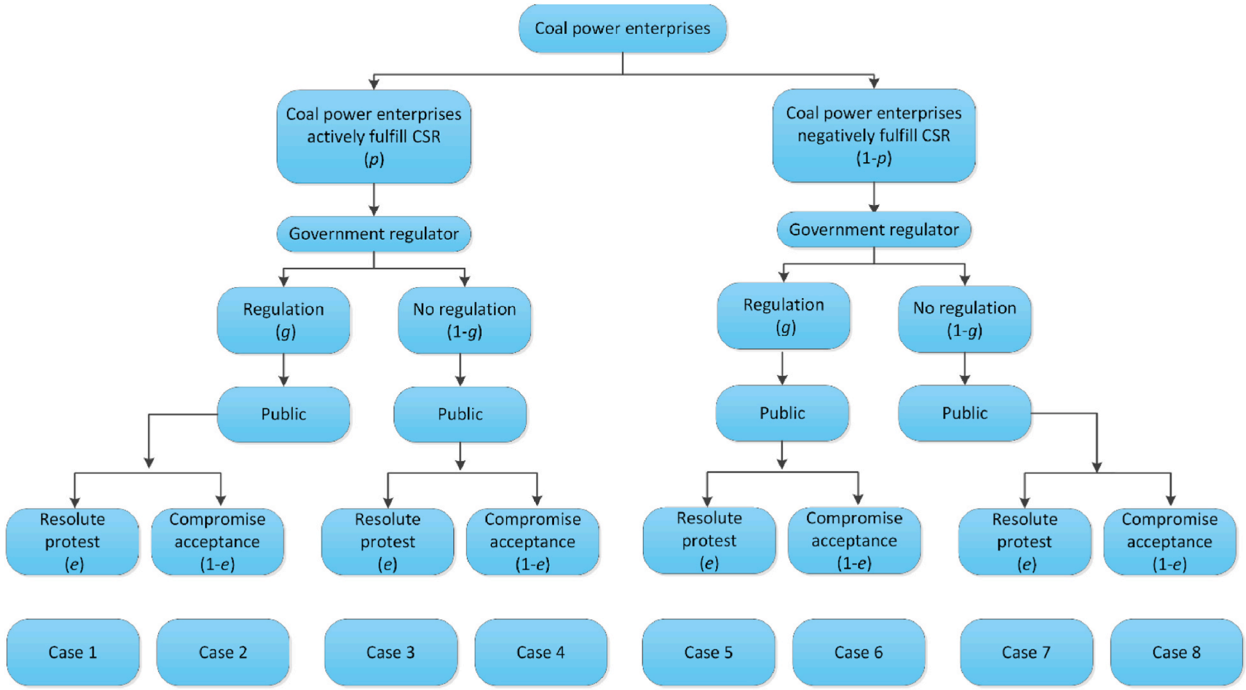



**Fig. 4.** Structural tree of the game model.

punishes the enterprises according to their specific performance; each party chooses to make the behavioral decision to maximize its own interests, and we assume that the strategy sets of each party are {Positive fulfillment of CSR; negative fulfillment of CSR}, {regulation; no regulation}, {resolute protest; compromise acceptance}.

Fig. 4 illustrates the results for all strategy combinations. Ideally, the strategy combination (Case 2) in which (coal power enterprises actively fulfill their social responsibility, government regulators choose to regulate, and the public chooses to accept) is optimal both for the effect of emission reduction and for maximizing social welfare. However, in practice, the theoretically optimal strategy combination does not always occur. For example, the coal power enterprises may be negative in fulfilling their social responsibility in order to save costs, and even if the government regulators actively fulfill its regulatory responsibility and the public choose to protest, it will not help (Case 6). When coal power enterprises actively fulfill its social responsibility to reduce emissions, the government regulators may choose not to regulate it and the public may not pay for it (Case 3), in which case coal power enterprises' efforts will be ignored, and in the long run, they will lose the internal drive to fulfill its social responsibility positively.

It is not difficult to find that coal and power enterprises, government regulators and the public may choose to act together because of the same interests, but in most cases, the potential interests of the three parties will conflict, which will lead to a deviation from the theoretical optimum in the strategic choices of the three parties. In the following, we will specifically analyze the model implications of the eight strategy combinations. We will explore the intrinsic reasons for the deviation of the three parties' strategy choices from the theoretical optimum, and design different schemes to promote the evolution of the three parties' strategy combinations towards the Pareto optimum.

### 4.3. Basic assumption

In order to better construct the game model to study the social responsibility behavior of coal power enterprises, the hypotheses are as follows:

Assumption 1.

In order to achieve fruitful results in the fulfillment of social responsibility, the symbiosis of coal and power industry is an effective way. Coal is the main source of resources for electric power enterprises, and electric power enterprises are the important destination of coal. With the cascade effect, both sides break down the industry barriers, and through the enhancement of complementarities and synergies brought about by the symbiotic system, the economic and environmental benefits are significantly enhanced. Therefore, in this paper, coal enterprises and electric power enterprises are regarded as a whole and collectively referred to as coal and power enterprises. All parties of the game are limited rational subjects, which is in line with the value perception feature of PT-MA theory.

Assumption 2.

The proportion of risk borne by the participants varies with the different strategy choices, and the system risk is lowest only when both coal and power enterprises and the public choose positive behaviors, i.e., {positively fulfilling CSR; compromising and accepting}. According to the principle of risk sharing, risk will be transferred from one subject to another relevant subject, and the degree of risk transfer is expressed in terms of the risk transfer coefficient. Coal and power enterprises provide electricity services to the public, and if there are problems within the coal and power enterprises, the systemic risk will also affect the public. Based on the principle of risk spillover, the degree of risk spillover is expressed by the risk spillover coefficient.

Assumption 3.

For coal and power enterprises, we assume that the loss of negative CSR fulfillment is greater than the loss of positive CSR fulfillment. Similarly, the loss of non-regulation by the government regulator is greater than the loss of regulation, and the loss of resolute protest by the public is greater than the loss of compromise acceptance.

### *4.4. Model construction*

According to the above assumptions, the benefit perception matrix of coal power enterprises, government and public groups can be obtained, as shown in Table 1.

The specific parameter settings of the gain perception matrix are shown in Table 2.

## 5. Model analysis

### *5.1. Strategy stability analysis*

#### *5.1.1. Strategy stability analysis of coal power enterprises*

The “positive CSR fulfillment" value perception $T1p$, “negative CSR fulfillment" value perception $T2p$, and average value perception of coal power enterprises $\overline{Tp}$ are respectively:

$$T1p = w(g)(P(WHa+R)-C(C1)) + w(1-g)(P(WHa)-C(C1+\varphi\psi Lw(q)))$$

$$\begin{aligned} T2p = {} & w(g)[w(e)(-C(C2+F+Dc+\psi Lw(q))) + w(1-e)(-C(C2+F+\psi Lw(q)))] \\ & + w(1-g)[w(e)(-C(C2+Dc+Lw(q))) + w(1-e)(-C(-C(C2+Lw(q)))] \end{aligned}$$

$$\overline{Tp} = pT1p + (1-p)T2p \tag{1}$$

The dynamic equation of coal power enterprises is as follows:

$$F(p) = dp/dt = p(T1p - \overline{Tp}) = p(1-p)(T1p - T2p) = p(1-p)$$
$$\left\{ \begin{aligned} & w(g)(P(WHa+R)-C(C1)) - w(g)[w(e)(-C(C2+F+Dc+\psi Lw(q))) + w(1-e) \\ & (-C(C2+F+\psi Lw(q)))] + w(1-g)(P(WHa)-C(C1+\varphi\psi Lw(q))) - w(1-g) \\ & [w(e)(-C(C2+Dc+Lw(q))) + w(1-e)(-C(C2+Lw(q)))] \end{aligned} \right\}$$

$$F(p) = p(1-p)[w(g)A + w(1-g)B] \tag{2}$$

$A$ denotes the difference between the positive and negative CSR value functions of coal power enterprises when they are regulated by government regulators; $B$ denotes the difference between the positive and negative CSR value functions of coal power enterprises when they are not regulated by government regulators.

#### *5.1.2. Strategy stability analysis of government regulators*

The “regulated" value perception $T1g$ and the “unregulated" value perception $T2g$ and the average value perception of the government regulators $\overline{Tg}$ are, respectively:

**Table 1**
Perceived matrix of Prospective revenue-payment value.

| | Public | | |
|---|---|---|---|
| | | Resolute protest $e$ | Compromise acceptance $1-e$ |
| Coal power enterprises actively fulfill CSR $p$ | Government regulators Regulation $g$ | $P(WHa+R)-C(C1)$<br>$P(Hb+Da)-C(C3+R)$<br>$P(Hd)-C(C4)$ | $P(R+WHa)-C(C1)$<br>$P(Hb+Da)-C(C3+R)$<br>$P(Hd)$ |
| | Government regulators No regulation $1-g$ | $P(WHa)-C(C1+\varphi\psi Lw(q))$<br>$P(Da)-C(Dd+\psi Lw(q))$<br>$P(Hc+Hd)-C(C4+\alpha L)$ | $P(WHa)-C(C1+\varphi\psi Lw(q))$<br>$P(Da)-C(\psi Lw(q))$<br>$P(Hd)-C(\alpha L)$ |
| Coal power enterprises negatively fulfill CSR $1-p$ | Government regulators Regulation $g$ | $-C(C2+F+Dc+\psi Lw(q))$<br>$P(Hb+F)-C(C3+Db+Dd+\varphi\psi Lw(q))$<br>$P(Hc)-C(C4+\alpha L)$ | $-C(C2+F+\psi Lw(q))$<br>$P(Hb+F)-C(C3+Db+\varphi\psi Lw(q))$<br>$-C(\alpha L)$ |
| | Government regulators No regulation $1-g$ | $-C(C2+Dc+Lw(q))$<br>$-C(Db+Dd+Lw(q))$<br>$P(Hc)-C(C4+L)$ | $-C(C2+Lw(q))$<br>$-C(Db+Lw(q))$<br>$-C(L)$ |

**Table 2**
Parameter symbols and their meanings.

| Parameter | Meaning |
|---|---|
| $p$ | Probability of active CSR fulfillment by coal power enterprises |
| $g$ | Probability of regulation by government regulators |
| $e$ | Probability of public protest |
| $C1$ | Cost of CSR fulfillment by coal power enterprises |
| $C2$ | Psychological cost of negative CSR fulfillment by coal power enterprises |
| $C3$ | Regulatory costs |
| $C4$ | Costs arising from resolute public protests |
| $W$ | Degree of Enhancement |
| $Ha$ | Unit gains (demand, reputation enhancement) available to coal power enterprises for positive CSR fulfillment |
| $Hb$ | Regulatory gains |
| $Hc$ | Gains from determined public protests |
| $Hd$ | Gains from public |
| $R$ | Rewards from government regulators for coal power enterprises that actively fulfill CSR |
| $F$ | Penalties from government regulators for coal power enterprises that negatively fulfill CSR |
| $Da$ | Gains (e.g., reputation, credibility, etc.) suffered by government regulators for proper regulation |
| $Db$ | Losses (e.g., reputation, credibility, etc.) suffered by government regulators due to improper regulation |
| $Dc$ | Losses to coal power enterprises from determined public protests (reputational losses) |
| $Dd$ | Losses to government from determined public protests (reputational losses) |
| $L$ | Accident risk |
| $\alpha$ | Risk spillover factor |
| $\varphi$ | Risk transfer coefficient |
| $\psi$ | Risk coefficient if only one party chooses positive behavior |
| $q$ | Probability of an accident occurring |

$$T1g = w(p)(P(Hb + Da) - C(C3+R)) + w(1-p)[w(e)(P(Hb+F) - C(C3+Db+Dd+\varphi\psi Lw(q))) + w(1-e)(P(Hb+F) - C(C3+Db+\varphi\psi Lw(q)))]$$

$$T2g = w(p)[w(e)(P(Da) - C(Dd+\psi Lw(q))) + w(1-e)(P(Da) - C(\psi Lw(q)))] + w(1-p)[w(e)(-C(Db+Dd+Lw(q))) + w(1-e)(-C(Db+Lw(q)))]$$

$$\overline{Tg} = gT1g + (1-g)T2g \tag{3}$$

The dynamic equation of government regulators is as follows:

$$F(g) = dg/dt = g(T1g - \overline{Tg}) = g(1-g)(T1g - T2g) = g(1-g)\left\{\begin{array}{l} w(p)(P(Hb+Da) - C(C3+R)) - w(p)[w(e)(P(Da) - C(Dd+\psi Lw(q))) + w(1-e)(P(Da) \\ -C(\psi Lw(q)))] + w(1-p)[w(e)(P(Hb+F) - C(C3+Db+Dd+\varphi\psi Lw(q)) \\ +w(1-e)(P(Hb+F) - C(C3+Db+\varphi\psi Lw(q)))] - w(1-p)[w(e)(-C(Db+Dd+Lw(q))) \end{array}\right\}$$

$$F(g) = g(1-g)[w(p)M + w(1-p)N] \tag{4}$$

$M$ denotes the difference between the value function of regulation by the government regulator and the value function of non-regulation by the government regulator when the coal power enterprises actively fulfill CSR; $N$ denotes the difference between the value function of regulation by the government regulator and the value function of non-regulation by the government regulator when the coal power enterprises negatively fulfill CSR.

### 5.1.3. Strategy stability analysis of public

The public's "firm protest" value perception $T1e$ and "compromise acceptance" value perception $T2e$ and the average value perception $\overline{Te}$ are:

$$T1e = w(p)[w(g)(P(Hd) - C(C4)) + w(1-g)(P(Hc+Hd) - C(C4+\alpha L))] + w(1-p)[w(g)(P(Hc) - C(C4+\alpha L)) + w(1-g)(P(Hc) - C(C4+L))]$$

$$T2e = w(p)[w(g)(P(Hd)) + w(1-g)(P(Hd) - C(\alpha L))] + w(1-p)[w(g)(-C(\alpha L)) + w(1-g)(-C(L))]$$

$$\overline{Te} = eT1e + (1-e)T2e \tag{5}$$

The dynamic equation of public is as follows:

$$F(e) = de/dt = e(T1e - \overline{Te}) = e(1-e)(T1e - T2e) = e(1-e)$$
$$\left\{\begin{array}{l} w(p)[w(g)(P(Hd) - C(C4)) + w(1-g)(P(Hc+Hd) - C(C4+\alpha L))] - w(p)[w(g)(P(Hd)) \\ +w(1-g)(P(Hd) - C(\alpha L))] + w(1-p)[w(g)(P(Hc) - C(C4+\alpha L)) + w(1-g)(P(Hc) \\ -C(C4+L))] - w(1-p)[w(g)(-C(\alpha L)) + w(1-g)(-C(L))] \end{array}\right\}$$

$$F(e) = e(1-e)[w(p)E + w(1-p)F] \tag{6}$$

$E$ denotes the difference between the value function of resolute public protest and the value function of public compromise acceptance when coal power enterprises actively fulfill CSR; $F$ denotes the difference between the value function of resolute public protest and the value function of public compromise acceptance when coal power enterprises negatively fulfill CSR.

## 5.2. Stability analysis of strategy portfolio

### 5.2.1. Construction of Jacobian matrix

The strategy choices of game subjects are not only affected by their own utility, but also by the influence of stakeholders. Therefore, it is more realistic to further analyze the stability of strategy portfolio on the basis of analyzing the stability of individual subject's strategy.

From Equations (1) and (2), it follows that the coal power enterprises can achieve local stability by choosing the strategy of "positive CSR fulfillment" when $p = 0$, $p = 1$.

From Equations (3) and (4), it follows that government regulators can achieve local stability by choosing the strategy of "regulated" when $g = 0$, $g = 1$.

From Equations (5) and (6), it follows that the public can achieve local stability by choosing the strategy of "firm protest" when $e = 0$, $e = 1$.

As a result, the eight local equilibria formed by the system are $E1(0,0,0)$, $E2(1,0,0)$, $E3(0,1,0)$, $E4(0,0,1)$, $E5(1,1,0)$, $E6(1,0,1)$, $E7(0,1,1)$ and $E8(1,1,1)$.

According to the stability analysis of the evolutionary game, the stability of the strategy portfolio of each game subject can be judged according to the Lyapunov indirect method. The Jacobian matrix of the replica dynamical system is:

$$J = \begin{bmatrix} \partial F(p)/\partial p \partial F(p)/\partial g \partial F(p)/\partial e \\ \partial F(e)/\partial p \partial F(e)/\partial g \partial F(e)/\partial e \\ \partial F(g)/\partial p \partial F(g)/\partial g \partial F(g)/\partial e \end{bmatrix} \tag{7}$$

From Equation (7), the strategy portfolio stability analysis is shown in Table 3.

The specific expressions of the parameters involved in Table 3 are as follows:

$$A = (P(WHa+R) - C(C1)) - [w(e)(-C(C2+F+Dc+\psi Lw(q))) + w(1-e)(-C(C2+F+\psi Lw(q)))]$$

$$B = (P(WHa) - C(C1+\varphi\psi Lw(q))) - [w(e)(-C(C2+Dc+Lw(q))) + w(1-e)(-C(C2+Lw(q)))]$$

$$M = (P(Hb+Da) - C(C3+R)) - [w(e)(P(Da) - C(Dd+\psi Lw(q))) + w(1-e)(P(Da) - C(\psi Lw(q)))]$$

$$N = w(e)(P(Hb+F) - C(C3+Db+Dd+\varphi\psi Lw(q))) + w(1-e)(P(Hb+F) - C(C3+Db+\varphi\psi Lw(q)))] - [w(e)( \\ -C(Db+Dd+Lw(q))) + w(1-e)(-C(Db+Lw(q)))]Db+Lw(q)))] - CDb+Dd+Lw(q))) + w(1-e)( \\ -C(Db+Lw(q)))]Db+Lw(q)))] - C - C$$

$$E = [w(g)(P(Hd) - C(C4)) + w(1-g)(P(Hc+Hd) - C(C4+\alpha L))] - [w(g)(P(Hd)) + w(1-g)(P(Hd) - C(\alpha L))]$$

$$F = [w(g)(P(Hc) - C(C4+\alpha L)) + w(1-g)(P(Hc) - C(C4+L))] - [w(g)(-C(\alpha L)) + w(1-g)(-C(L))]$$

**Table 3**
Strategy portfolio stability analysis.

| Equilibrium point | Eigenvalue $\lambda1, \lambda2, \lambda3$ | Symbol | Stability |
|---|---|---|---|
| (0,0,0) | $B, N, F$ | ( × , × , × ) | Stable when ① is satisfied |
| (1,0,0) | $-B, M, E$ | ( × , × , × ) | Stable when ② is satisfied |
| (0,1,0) | $A, -N, F$ | ( × , × , × ) | Stable when ③ is satisfied |
| (0,0,1) | $B, N, -F$ | ( × , × , × ) | Stable when ④ is satisfied |
| (1,1,0) | $-A, -M, E$ | ( × , × , × ) | Stable when ⑤ is satisfied |
| (1,0,1) | $-B, M, -E$ | ( × , × , × ) | Stable when ⑥ is satisfied |
| (0,1,1) | $A, -N, -F$ | ( × , × , × ) | Stable when ⑦ is satisfied |
| (1,1,1) | $-A, -M, -E$ | ( × , × , × ) | Stable when ⑧ is satisfied |

#### 5.2.2. Scenario discussions

It can be seen that when the parameters in Table 3 change, the evolutionary stabilization strategy of this game will also change, and the different scenarios will be discussed below.

**Scenario 1:** When condition ① is satisfied, i.e.:

$$\begin{cases} B = (P(WHa) - C(C1+\varphi\psi Lw(q))) - [w(e)( - C(C2+Dc + Lw(q))) + w(1-e)( - C(C2+Lw(q)))] < 0N \end{cases}$$

$$= w(e)(P(Hb+F) - C(C3+Db+Dd+\varphi\psi Lw(q))) + w(1-e)(P(Hb+F) - C(C3+Db+\varphi\psi Lw(q)))] - [w(e)( - C(Db+Dd + Lw(q)))+w(1-e)( - C(Db+Lw(q)))] < 0Db+Lw(q)))] < 0-CDb+Dd+Lw(q)))+w(1-e)( - C(Db+Lw(q)))] < 0Db + Lw(q)))] < 0-C-CF$$

$$= [w(g)(P(Hc) - C(C4+\alpha L)) + w(1-g)(P(Hc) - C(C4+L))] - [w(g)(-C(\alpha L)) + w(1-g)(-C(L))] < 0$$

In this scenario, point (0,0,0) is the stabilization point of the replica dynamic system. At this time, the value perception gain of coal power enterprises in negatively performing CSR is greater than the value perception gain of positively performing CSR, in this case, the value perception of government regulators not regulating and the value perception gain of the public compromising and accepting occupy the dominant position of their respective rationality, and the whole evolution game reaches equilibrium, i.e., the evolutionary stabilization strategy is (negative performance of CSR, no regulation by the government regulators, and the public compromising and accepting).

At this time, due to cost sensitivity and optimism bias, coal power enterprises know that negative CSR fulfillment may cause corporate reputation and economic losses, and still choose to negatively fulfill their social responsibility with the fluke that a low percentage of incidents will not happen, and government regulators choose not to regulate, and the public choose to accept this status quo due to the setting of a lower reference point.

**Scenario 2:** When condition ② is satisfied, i.e.:

$$\begin{cases} B = (P(WHa) - C(C1+\varphi\psi Lw(q))) - [w(e)( - C(C2+Dc + Lw(q))) + w(1-e)( - C(C2+Lw(q)))] > 0 \\ M = (P(Hb+Da) - C(C3+R)) - [w(e)(P(Da) - C(Dd+\psi Lw(q))) + w(1-e)(P(Da) - C(\psi Lw(q)))] < 0 \\ E = [w(g)(P(Hd) - C(C4)) + w(1-g)(P(Hc+Hd) - C(C4+\alpha L))] - [w(g)(P(Hd)) + w(1-g)(P(Hd) - C(\alpha L))] < 0 \end{cases}$$

In this scenario, point (1,0,0) is the stabilization point of the replica dynamic system. At this point, although the government regulator does not regulate, the current perceived benefits of the coal power enterprises can still motivate the enterprises to actively fulfill the CSR, and the public will also choose the "compromise and acceptance" strategy. Therefore, the final evolutionary stabilization strategy is (actively perform CSR, the government regulator does not regulate, and the public accepts the compromise).

At this point, coal power enterprises overcome their cost sensitivity and optimism bias and choose to actively fulfill their social responsibilities. To save costs, government regulators and the public choose to rely on the self-discipline of coal power enterprises rather than taking additional actions.

**Scenario 3:** When condition ③ is satisfied, i.e.:

$$\begin{cases} A = (P(WHa+R) - C(C1)) - [w(e)( - C(C2+F+Dc+\psi Lw(q))) + w(1-e)( - C(C2+F+\psi Lw(q)))] < 0N \end{cases}$$

$$= w(e)(P(Hb+F) - C(C3+Db+Dd+\varphi\psi Lw(q))) + w(1-e)(P(Hb+F) - C(C3+Db+\varphi\psi Lw(q)))] - [w(e)( - C(Db+Dd + Lw(q)))+w(1-e)( - C(Db+Lw(q)))] > 0Db+Lw(q)))] > 0-CDb+Dd+Lw(q)))+w(1-e)( - C(Db+Lw(q)))] > 0Db + Lw(q)))] > 0-C-CF$$

$$= [w(g)(P(Hc) - C(C4+\alpha L)) + w(1-g)(P(Hc) - C(C4+L))] - [w(g)(-C(\alpha L)) + w(1-g)(-C(L))] < 0$$

In this scenario, point (0,1,0) is the stabilization point of the replicated dynamic system. At this point, the value-perceived gain of the coal and power enterprises in negatively fulfilling CSR is greater than their value-perceived gain in positively fulfilling CSR, the value-perceived gain of the government regulator in regulating is greater than its value-perceived gain in not regulating, and the value-perceived gain of the public in compromising and accepting is greater than its value-perceived gain in resolutely protesting. Therefore, the final evolutionary stabilization strategy is (negative fulfillment of CSR, regulation by government regulators, and compromise acceptance by the public).

At this point, the government regulators overcome the cost sensitivity and optimism bias and choose to regulate. Due to cost sensitivity and optimism bias, coal power enterprises know that negative CSR fulfillment may cause corporate reputation and economic losses, but still choose to negatively fulfill their social responsibility with the fluke that a low percentage of incidents will not happen. The public choose to accept this status quo due to the low reference point set.

**Scenario 4:** When condition ④ is satisfied, i.e.:

$$\begin{cases} B = (P(WHa) - C(C1+\varphi\psi Lw(q))) - [w(e)( - C(C2+Dc + Lw(q))) + w(1 - e)( - C(C2+Lw(q)))] < 0N \end{cases}$$

$$= w(e)(P(Hb + F) - C(C3+Db + Dd + \varphi\psi Lw(q))) + w(1 - e)(P(Hb + F) - C(C3+Db + \varphi\psi Lw(q)))] - [w(e)( - C(Db + Dd + Lw(q))) + w(1 - e)( - C(Db + Lw(q)))] < 0Db + Lw(q)))] < 0 - CDb + Dd + Lw(q))) + w(1 - e)( - C(Db + Lw(q)))] < 0Db + Lw(q)))] < 0 - C - CF$$

$$= [w(g)(P(Hc) - C(C4+\alpha L)) + w(1 - g)(P(Hc) - C(C4+L))] - [w(g)(-C(\alpha L)) + w(1 - g)(-C(L))] > 0$$

In this scenario, point (0,0,1) is the stabilization point of the replica dynamic system. At this point, the value perception gain of coal and power enterprises negatively performing CSR is dominant, and the gain of government regulators “not regulating" is greater than the gain of “regulating", which will result in the situation of coal and power enterprises negatively performing CSR and government regulators not regulating, and after a long time evolution, the public will choose to accept the CSR. After long-term evolution, the public will choose the “resolute protest" strategy. Therefore, the final evolutionary stable strategy is (negative CSR fulfillment, no regulation by government regulators, and public protest).

At this time, due to cost sensitivity and optimism bias, coal power enterprises know that negative CSR fulfillment may cause corporate reputation and economic losses, but still choose to negatively fulfill their social responsibility with the fluke that a low percentage of incidents will not occur. Government regulators choose to rely on the self-discipline of coal and power enterprises and the supervision of the public instead of regulating them. The public choose to resist in order to avoid potential risks.

**Scenario 5:** When condition ⑤ is satisfied, i.e.:

$$\begin{cases} A = (P(WHa + R) - C(C1)) - [w(e)( - C(C2+F + Dc + \psi Lw(q))) + w(1 - e)( - C(C2+F + \psi Lw(q)))] > 0 \\ M = (P(Hb + Da) - C(C3+R)) - [w(e)(P(Da) - C(Dd + \psi Lw(q))) + w(1 - e)(P(Da) - C(\psi Lw(q)))] > 0 \\ E = [w(g)(P(Hd) - C(C4)) + w(1 - g)(P(Hc + Hd) - C(C4+\alpha L))] - [w(g)(P(Hd)) + w(1 - g)(P(Hd) - C(\alpha L))] < 0 \end{cases}$$

In this scenario, point (1,1,0) is the stabilization point of the replicated dynamic system. At this time, the value perception of coal and power enterprises actively performing CSR is higher than the value perception of negatively performing CSR, in this case, the benefit of government regulators “regulating" is higher than “not regulating", and the benefit of the public “compromising and accepting" is higher than the benefit of their protests. In this case, the benefit of government regulators “regulating" is higher than “not regulating", and the benefit of the public “compromising and accepting" is higher than “firmly protesting". Therefore, the final evolutionary stabilization strategy is (active implementation of CSR, regulation by the government regulator, and acceptance by the public).

At this point, coal power enterprises overcame their sensitivity to costs and optimism bias and choose to actively fulfill their social responsibilities, and government regulators overcome their sensitivity to costs and optimism bias and choose to regulate. The public choose not to take additional action due to cost avoidance.

**Scenario 6:** When condition ⑥ is satisfied, i.e.:

$$\begin{cases} B = (P(WHa) - C(C1+\varphi\psi Lw(q))) - [w(e)( - C(C2+Dc + Lw(q))) + w(1 - e)( - C(C2+Lw(q)))] > 0 \\ M = (P(Hb + Da) - C(C3+R)) - [w(e)(P(Da) - C(Dd + \psi Lw(q))) + w(1 - e)(P(Da) - C(\psi Lw(q)))] < 0 \\ E = [w(g)(P(Hd) - C(C4)) + w(1 - g)(P(Hc + Hd) - C(C4+\alpha L))] - [w(g)(P(Hd)) + w(1 - g)(P(Hd) - C(\alpha L))] > 0 \end{cases}$$

In this scenario, point (1,0,1) is the stabilization point of the replica dynamical system. This means that when the value-perceived gain of the coal and power enterprises' active fulfillment of CSR is greater than their value-perceived gain of negative fulfillment of CSR, the value-perceived gain of the government regulator's non-regulation is greater than its value-perceived gain of regulation, and the value-perceived gain of the public's resolute protests is greater than its value-perceived gain of compromised acceptance, then the whole system achieves the equilibrium state, and the final evolutionary stabilization strategy is (active fulfillment of CSR. government regulators do not regulate, and the public resolutely protests).

At this point, coal power enterprises overcome their cost sensitivity and optimism bias and choose to actively fulfill their social responsibility. To save costs, government regulators choose to rely on the self-discipline of coal power enterprises without taking additional actions. As a result of setting a higher reference point, the public had higher expectations of the government regulators, and even though the coal and power enterprises actively fulfilled their social responsibilities, the public still choose to boycott in order to express their dissatisfaction with the government regulators.

**Scenario 7:** When condition ⑦ is satisfied, i.e.:

$$\begin{cases} A = (P(WHa+R) - C(C1)) - [w(e)(-C(C2+F+Dc+\psi Lw(q))) + w(1-e)(-C(C2+F+\psi Lw(q)))] < 0N \\ \end{cases}$$

$$= w(e)(P(Hb+F) - C(C3+Db+Dd+\varphi\psi Lw(q))) + w(1-e)(P(Hb+F) - C(C3+Db+\varphi\psi Lw(q)))] - [w(e)(-C(Db+Dd + Lw(q))) + w(1-e)(-C(Db+Lw(q)))] > 0Db+Lw(q)))] > 0 - CDb+Dd+Lw(q))) + w(1-e)(-C(Db+Lw(q)))] > 0Db + Lw(q)))] > 0 - C - CF$$

$$= [w(g)(P(Hc) - C(C4+\alpha L)) + w(1-g)(P(Hc) - C(C4+L))] - [w(g)(-C(\alpha L)) + w(1-g)(-C(L))] > 0$$

In this scenario, point (0,1,1) is the stabilization point of the replica dynamic system. At this point, the value-perceived gain of the coal and power enterprises in negatively fulfilling CSR is greater than their value-perceived gain in positively fulfilling CSR, the value-perceived gain of the government regulator in regulating is greater than its value-perceived gain in not regulating, and the value-perceived gain of the public in resolutely protesting is greater than its value-perceived gain in compromising and accepting, which results in an ensemble of strategies for making the three-party game evolve to a stable state as (negatively fulfilling CSR, regulating, resolutely protesting). Resolute protest).

At this point, the government regulators overcome the cost sensitivity and optimism bias and choose to regulate. Due to the cost sensitivity and optimism bias, coal power enterprises know that negative CSR fulfillment may cause corporate reputation and economic losses, but still choose to negatively fulfill their social responsibility with the fluke that a low percentage of incidents will not happen. The public choose to boycott in order to avoid potential risks.

**Scenario 8:** When the condition ⑧ is satisfied, i.e.:

$$\begin{cases} A = (P(WHa+R) - C(C1)) - [w(e)(-C(C2+F+Dc+\psi Lw(q))) + w(1-e)(-C(C2+F+\psi Lw(q)))] > 0 \\ M = (P(Hb+Da) - C(C3+R)) - [w(e)(P(Da) - C(Dd+\psi Lw(q))) + w(1-e)(P(Da) - C(\psi Lw(q)))] > 0 \\ E = [w(g)(P(Hd) - C(C4)) + w(1-g)(P(Hc+Hd) - C(C4+\alpha L))] - [w(g)(P(Hd)) + w(1-g)(P(Hd) - C(\alpha L))] > 0 \end{cases}$$

In this scenario, point (1,1,1) is the stabilization point of the replica dynamic system. At this time, the coal and power enterprises to actively fulfill CSR, government regulators to regulate and the public's value perception of resolute protests are at a high level, the replica system is ultimately stabilized at (coal and power enterprises to actively fulfill CSR, government regulators to regulate and the public to resolutely protest).

At this point, government regulators overcome their cost sensitivity and optimism bias and choose to regulate, and the coal power enterprises overcome their cost sensitivity and optimism bias and choose to actively fulfill their social responsibility. The public is still not satisfied with the behavior of government regulators and coal power enterprises because they have set a higher reference point.

### 5.3. *Analysis of results*

Based on the above argumentation, the game system reaches the theoretical optimal state when the behavioral strategies of the game subjects are (actively performing CSR, not regulating, and compromising and accepting), and the well-being of people's livelihoods can be safeguarded by virtue of the high degree of self-regulation of coal and power enterprises, and social welfare can be maximized with the least occupation of public resources. However, in line with the objective facts, this state should be the highest-order form. In reality, when the value-perceived benefits of the coal and power enterprises actively performing CSR, the government regulator supervising and the public compromising and accepting are greater than the value-perceived benefits of their antagonistic behaviors, the system reaches the evolutionary optimal state. At this time, there are still cost, perceived value, risk appetite and other factors will impede the system to the equilibrium state of evolution; only with limited rationality of the game subject, its fluke mentality leads to the decision-making process of the judgment bias, will also make the system deviate from the optimal stable state. The specific analysis is as follows.

(1) Cost-efficiency perception bias

The cost perception of CSR performance of coal power enterprises, supervision by government regulators and public acceptance of compromise is often higher than the cost perception of their opposing behaviors, and similarly, the utility perception of CSR performance of coal power enterprises, supervision by government regulators and public acceptance of compromise is lower than that of their opposing behaviors. For coal power enterprises, the cost of CSR fulfillment is increasing under the effect of technological innovation, resource coordination and other factors, but the benefits and reputation enhancement brought by the actual behavior are lagging behind, and cannot meet their psychological expectations in the short term, so out of the consideration of the "economic man", their strategic choices will be inclined to "For the government, the cost of formulating and implementing a complicated regulatory system is much higher than the credibility-enhancing benefits of improving the environment and the quality of life of the residents, which will frustrate the government's management motivation. In addition, with the self-discipline of coal and power enterprises and public supervision, the government can still achieve the same regulatory effect while saving costs and reducing its own regulatory pressure, which is a good choice; for the public, the ability and quality of power supply can not be guaranteed, the basic demands of life can not be met, and the increasing degree of environmental damage continues to break through the threshold of people's rationality and emotion, and the perceived benefits brought by the protests can be considerable, and the public can not be satisfied. For the public, the perceived benefits of protesting are considerable, and the public's strategic choice of “resolute protesting" has been strengthened by the trade-offs.

(2) Optimism Bias

Under the subjective cognition of the game subjects, the probability of government regulation, the probability of the risk of “free-riding" or “greenwashing" being detected, and the probability of public protests are usually underestimated, and the possible adverse consequences are ignored because of the decision-maker's overconfidence, and the awareness of risk avoidance is weak. Awareness of risk avoidance is weak. Coal power enterprises try to cover up or divert the public's attention from their inherent lack of social responsibility through charitable and community giving, etc., knowing that negative CSR fulfillment may cause corporate reputation and economic losses, but still holding a low percentage of incidents will not happen.

(3) Risk Appetite

The reflexive effect of prospect theory suggests that people's preferences for gains and losses are asymmetric, with a tendency to be risk-averse when faced with the prospect of possible gains, and vice versa with a tendency to be risk-seeking. Coal power enterprises, the government and the public, as the limited rational decision-making subjects of this game system, have obvious risk preferences, which are manifested in the fact that the three parties of the game are more inclined to take risks to choose high-risk and high-return strategies when the costs of active fulfillment of the CSR, regulation and acceptance of compromise are certain but the environmental damage and the surge of the public protests are uncertain.

(4) Value Perception Reference Points

Decision makers establish different reference points in the revenue value perception account and payment value perception account by virtue of various subjective criteria, and higher psychological expectations tend to result in high price and low cost reference points. At this time, the decision-making group has a strong sensitivity to the perception of price difference, which increases their tendency to choose negative behaviors, and is not conducive to the formation of the strategy of “active fulfillment of CSR" by coal and power enterprises, “supervision" by government regulators, and “compromise and acceptance" by the public. The strategy of “compromise and acceptance" by the public.

## 6. Simulation analysis

In order to more intuitively understand the change of strategy selection of the game parties, Matlab is used to carry out simulation analysis of the evolutionary game to explore the influence of each key factor on the behavioral strategy of the game subject.

The initial settings and basis of specific parameters are shown in Table 4.

### 6.1. The effect of the degree of accident risk spillover on the evolutionary outcome

Taking $\{\alpha L = 2.5, \alpha L = 5, \alpha L = 10\}$ , the evolutionary path of the gaming system is shown in Fig. 5.

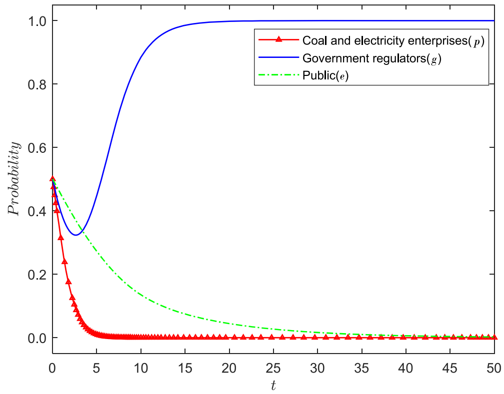
Fig. 5(a)–(c) shows that when the degree of risk spillover is small, the strategy of coal and power enterprises evolves towards “negative CSR fulfillment", and the strategy of the public evolves towards “compromise and acceptance"; as the degree of risk spillover increases, the coal and power enterprises and the government regulators experience a certain degree of fluctuation and then stabilize in the positive direction, i.e., positive CSR fulfillment and regulation. With the increase of risk spillover, both coal power enterprises and government regulators experience a certain degree of fluctuation and then stabilize in the positive direction, i.e., actively fulfilling CSR and regulation, but the public's tendency to choose protesting behavioral strategies increases when they perceive that risky accidents bring too much negative impact.

This is consistent with the conclusion in literature [42] that “risk spillover can prompt external stakeholders to take positive measures". Therefore, appropriately increasing the degree of risk spillover is conducive to improving the fulfillment of CSR by coal power enterprises as well as the management motivation of government regulators.

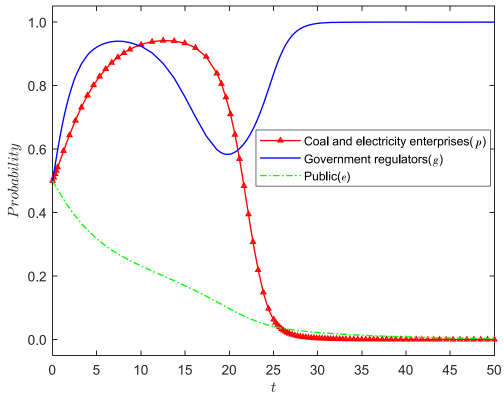
**Table 4**
Initial parameter settings and basis.

| Parameter | $p$ | $e$ | $g$ | $C1$ | $C2$ | $C3$ | $C4$ | $W$ | $Ha$ | $Hb$ | $Hc$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Initial value | 0.5 | 0.5 | 0.5 | 4 | 1 | 2 | 1 | 1 | 1 | 1.5 | 2 |
| Parameter | $Hd$ | $R$ | $F$ | $Da$ | $Db$ | $Dc$ | $Dd$ | $L$ | $\varphi$ | $\alpha$ | $\psi$ |
| Initial value | 1 | 2 | 2 | 1 | 2 | 2 | 2 | 5 | 0.2 | 0.5 | 0.5 |
| Parameter | $q$ | $U0$ | $U1$ | $\beta$ | $\theta$ | $\nu$ | $\sigma$ | $\lambda$ | $\delta$ | | |
| Initial value | 0.03 | 1 | 1 | 0.88 | 0.88 | 0.98 | 0.98 | 2.5 | 2.5 | | |

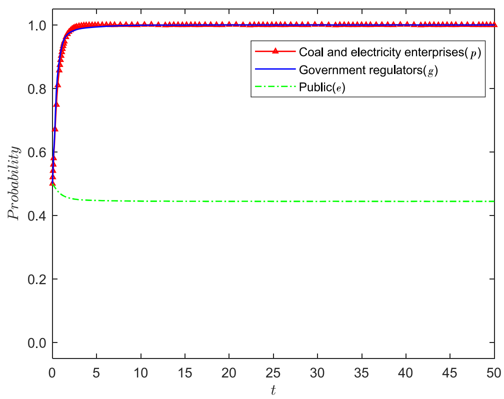
Parameter settings are based on randomized experimental data from scholars Gurevich, Tversky, and others.




(a)




(b)




(c)

**Fig. 5.** Impact of accident risk spillover on the evolution of each party's strategy.

### 6.2. *Influence of reference points on evolutionary results*

Taking $\{U0 = 0.5, U0 = 1.0, U0 = 1.5\}$, $\{U1 = 0.5, U1 = 1.0, U1 = 1.5\}$ , the evolutionary path of the gaming system is shown in Fig. 6.

As can be seen from Fig. 6(a)–(b), with the decrease of the utility reference point, the behavioral strategies of the game parties evolve rapidly towards the stable equilibrium state, and with the increase of the cost reference point, the strategy evolution rate of the game subject slows down firstly and then speeds up.

This is consistent with Heath's research [43], in which Heath suggests that the value of a $5 discount depends on whether the item is priced at $10 or $500, i.e., different reference points will lead to different comparison results. Therefore, the change of the utility

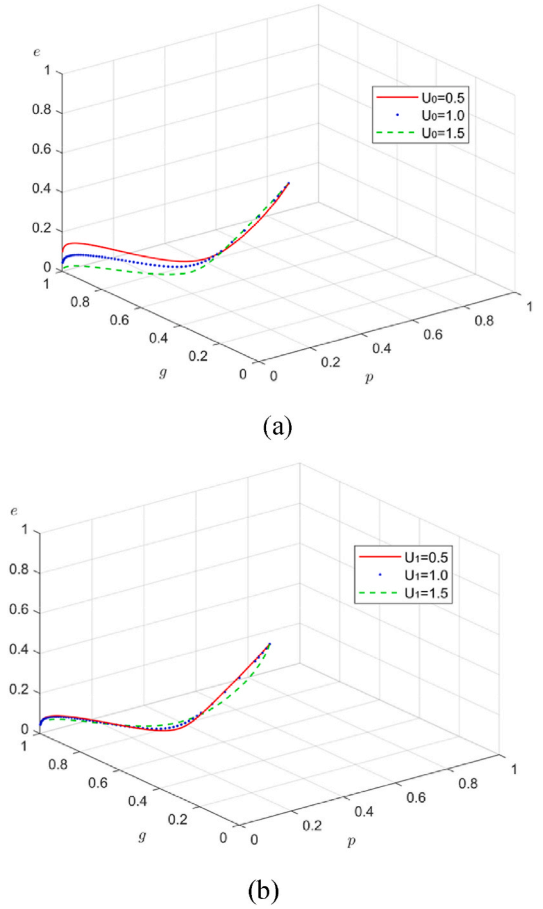



**Fig. 6.** Influence of reference point on the strategy evolution of each party.

reference point and cost reference point can promote the evolution of the game system to stabilize, and compared with adjusting the cost reference point, adjusting the utility stabilization point is more effective.

### *6.3. Effects of fulfillment cost and psychological cost on evolutionary outcomes*

Taking $\{C1 = 4, C1 = 3, C1 = 2\}$, $\{C2 = 1, C2 = 3, C2 = 6\}$, the evolutionary path of the game system is shown in Fig. 7.

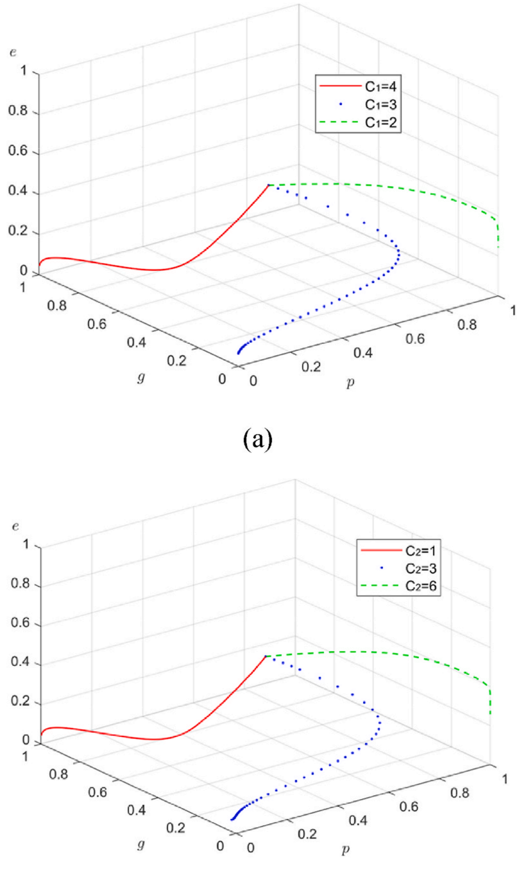
From Fig. 7(a)–(b), it can be seen that as the cost of CSR fulfillment decreases, the strategic choice of coal power enterprises gradually evolves to p = 1 (i.e., choosing positive CSR fulfillment strategy), and the government regulator will reduce the regulatory efforts until no regulation; when the psychological cost of negative CSR fulfillment increases, the enterprises will have a high probability of switching their behavioral strategy to positive CSR fulfillment, and the probability of governmental regulation will be reduced accordingly. Therefore, the decrease of fulfillment cost and the increase of psychological cost will help the coal power enterprises choose to fulfill CSR positively more often, and the regulatory pressure of the government will be reduced.

### *6.4. Impact of cost-loss aversion sensitivity on evolutionary outcomes*

Taking $\{\delta = 0.5, \delta = 1.5, \delta = 2.5\}$ , the evolutionary path of the game system is shown in Fig. 8.

As can be seen from Fig. 8, as the cost loss avoidance sensitivity decreases, the probability of coal power enterprises choosing to actively fulfill CSR strategies increases significantly and eventually stabilizes at 1. When the cost loss avoidance sensitivity increases, the public will have a certain psychological expectation of the cost loss, and the probability of choosing a protest strategy subsequently decreases to a lesser extent.

Literature [44] constructs a gambling experiment, in which the probability of winning \$20 is 50 % and the probability of losing \$10 is 50 %. The experimental results show that the attitude of most subjects is not to participate. This experiment shows the influence of loss aversion on behavior. Our results are consistent with this experiment. It can be seen that changing the cost loss avoidance sensitivity can help to prompt the coal power enterprises' strategy choices evolve towards active fulfillment of CSR, and also change the public's protest sentiment.




(a)

(b)

**Fig. 7.** Impact of cost on strategy evolution of each party.

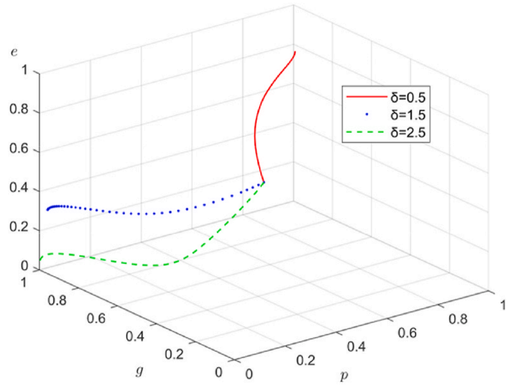



**Fig. 8.** Impact of cost-loss aversion sensitivity on the evolution of each party's strategy.

### 6.5. Impacts of the increased benefits of fulfilling CSR on the evolutionary outcomes

Taking $\{WHa = 1, WHa = 5, WHa = 10\}$, the evolution path of the gaming system is shown in Fig. 9.

As can be seen from Fig. 9(a)–(c), the enhancement of earnings from CSR fulfillment can enhance the confidence and robustness of coal and power enterprises in actively fulfilling CSR. When the gain from CSR fulfillment is low, all parties in the game aim at maximizing their own interests, and the stable strategies of coal power enterprises, government regulators and the public are negative CSR fulfillment, no regulation and resolute protest, respectively. With the increasing degree of CSR gain, the probability of CSR

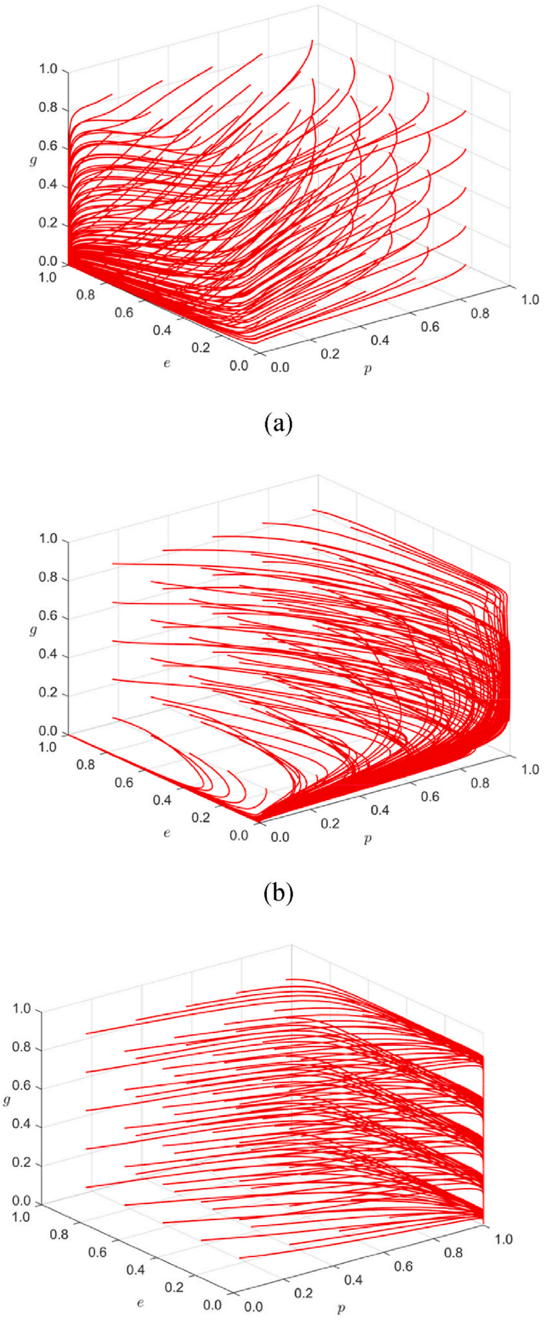



**Fig. 9.** Impact of fulfillment of CSR gain enhancement on the evolution of parties' strategies.

fulfillment by coal power enterprises and public compromise acceptance significantly increases, and evolves toward the optimal ideal stable state without relying on government regulation.

This is consistent with the conclusion in Literature [45] that "for a coal power enterprise to realize spontaneous green transformation, it must achieve spontaneous profitability before removing policy incentives". Therefore, enhancing the gains of fulfilling CSR can promote the stable evolution of coal power enterprises and public behavior in a positive direction.

## 7. Conclusions and management insights

### 7.1. Conclusions

Based on the PT-MA theory, this paper nonlinearly extends the evolutionary game model and analyzes the evolutionary law of social responsibility behavior of coal power enterprises, and the main conclusions of this study are shown as follows.

(1) The social responsibility behavior of coal power enterprises under the dual-carbon background is a typical cost-driven behavior, and coal power enterprises are more sensitive to costs compared to benefits [46]. Coal power enterprises will choose to actively fulfill their social responsibility only when they overcome their sensitivity to costs and optimism bias, otherwise they will not take additional actions.
(2) The formulation of regulatory strategies by government regulators depends largely on the decision-making inertia of coal and power enterprises. When the strategy choice of coal and power enterprises is stable in actively fulfilling social responsibility, the game system is stable no matter which regulatory strategy the government regulators choose. At the same time, when the regulators' strategic choices are stabilized at no regulation, the internal drive of coal and power enterprises to actively fulfill their social responsibility decreases [47].
(3) The public's choice of strategy does not entirely depend on the strategy choices of coal and power enterprises and government regulators, but is more closely related to the setting of the reference point [48]. When the public set a high reference point, even if the coal and power enterprises and government regulators chose positive strategies, the public would choose to boycott because the expected results could not be met. When the public set a lower reference point, even if both coal and power enterprises and government regulators chose negative strategies, the public would choose to accept the status quo.
(4) In addition to practical factors, subjective factors are also important factors affecting the fulfillment of social responsibility of coal power enterprises. Under limited rationality, the attitude of coal power enterprises towards risk is not completely neutral [49], and the risk preferences and decision-making preferences of coal power enterprises will significantly change the "relative weight" of objective benefits and costs, which in turn affects the fulfillment of social responsibility.

### 7.2. Management insights

The study shows that the optimal equilibrium state of the three-party game will be reached only when the coal and power enterprises actively fulfill their corporate social responsibility, the government regulators choose to regulate, and the public compromise and accept the situation, but in practice, there are eight combinations of strategies in the three-party game, and each combination of strategies may occur. In order to stabilize the equilibrium result of the three-party game in the optimal equilibrium state, the specific path is as follows.

(1) Regulating risk awareness and risk preference. The risks faced by coal power enterprises in poorly performing CSR are specifically manifested in the environmental pollution caused by poor low-carbon emission reduction, and the damage to corporate image and business credit caused by insufficient protection of people's basic demands. Establishing a perfect regulatory mechanism to improve the irrational phenomenon of "high cost of compliance and low cost of violation" while increasing the degree of spillover of the above risks will help enterprises to establish a correct awareness of risks and enhance the initiative of CSR fulfillment [36].
(2) Changing the value of factors affecting the cost-effectiveness of CSR behavior. Decision-makers' behavioral choices are based on the perceived cost-value of behavior, not the cost-value itself [50], and adjustments to the elements affecting the cost-value of CSR performance can accelerate the speed at which the gaming system reaches stability. Specifically, it includes increasing the cost reference point that affects the negative fulfillment of CSR, non-regulation and resolute protest behavior, decreasing the utility reference point that affects the negative fulfillment of CSR, regulation and compromise acceptance behavior, appropriately adjusting the sensitivity of cost-loss avoidance to prompt the coal and power enterprises to actively fulfill the CSR, strengthening the regulatory efforts of the governmental departments, and increasing the probability of the public's compromise acceptance.
(3) Reduce fulfillment costs and enable self-generated profitability of coal power enterprises. Further improve the government's reward and punishment system, appropriately increase the penalties for negative CSR fulfillment enterprises [51], while increasing the subsidies for positive behaviors [52], and enhance the fulfillment motivation of enterprises through policy incentives. As the real carrier of CSR fulfillment, enterprises themselves should strengthen the inculcation and cultivation of ethical thinking, enhance the employees' sense of identification with CSR, promote the strategic implementation of CSR, and increase the psychological expectation of the loss of government regulation and public protest costs.
(4) Disclosure of favorable information on CSR fulfillment by enterprises [28]. The lack of motivation for CSR fulfillment by coal power enterprises is greatly due to the fact that CSR is both highly costly, uncertain and lagging in benefit returns. Through the effective disclosure of CSR, enterprises with better performance will have positive changes in their economic benefits. At the same time, impression management and "free-riding" on social responsibility reports for self-interested motives can be avoided to a certain extent, thus enhancing the willingness of enterprises to actively fulfill CSR. In addition, with smooth communication among enterprises, the government and the public, the possibility of collective protests by the public will be reduced, and the

government will be able to carry out targeted supervision based on the performance of enterprises, thus optimizing the allocation of social resources.

(5) First, the government should take the initiative to lead the regularized communication mechanism with enterprises, build an intermediary platform for dialogue and consultation between the government and enterprises, and promote mutual understanding and full communication between the two sides. Second, an effective information sharing and communication mechanism should be established between stakeholders to realize the efficient matching of information flow and capital flow, and to guide the stakeholders in the fulfillment of social responsibility of coal and power enterprises to achieve a win-win situation through negotiation. Finally, government regulators should continuously enrich the public information access channels, improve the feedback mechanism, so that the public at the back end of the information dissemination chain can also express their demands in a timely and effective manner, and explore the construction of a synergistic governance model involving government regulators, industries, enterprises, public participation and social supervision [36].

### 7.3. Limitations

The following points can be considered for further development in future research：

(1) This paper only studies the fulfillment of social responsibility of coal power enterprises from a macro perspective, considering that the social responsibility of coal power enterprises includes multiple dimensions such as shareholders, consumers, natural environment, etc., the social responsibility of coal power enterprises can be researched based on different dimensions in the next step of research.

(2) This study only considered coal as the source of energy consumption for electric power enterprises, and in future studies, multiple energy sources can be considered as sources of energy consumption for electric power enterprises at the same time, and the energy-saving and emission reduction behaviors of coal power enterprises can be studied when there are competitive relationships.

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## Data availability statement

Data associated with the study has not been deposited into a publicly available repository.
Data will be made available on request.
No additional information is available for this paper.

## CRediT authorship contribution statement

**Bang Guo:** Writing – original draft. **Yixin Li:** Writing – review & editing. **Xinping Wang:** Writing – review & editing.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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