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Suan Sunandha Rajabhat University,
Thailand

*CORRESPONDENCE
Yu Hao,
haoyu_he@163.com
Chaolun Sun,
suncl@hpu.edu.cn

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Evolutionary game and simulation analysis on management synergy in China's coal emergency coordination

Peizhe Shi[1,2], Yu Hao[1,2,3]*, Chaolun Sun[3]* and LiJun Zhang[1,2]

[1]Safety and Emergency Management Research Center, Henan Polytechnic University, Jiaozuo, China, [2]Emergency Management School, Henan Polytechnic University, Jiaozuo, China, [3]State Key Laboratory Cultivation Base for Gas Geology and Gas Control, Henan Polytechnic University, Jiaozuo, China

Once coal mine accidents occur, a series of chain reactions will bring radiation effects that are difficult to solve in the short term to the normal operation of the economy and society. Therefore, the post-disaster management of coal mine accident is particularly important. Coal mine emergency response involves many stakeholders, and it needs various regions, departments to achieve multi-agent, multi-level effective collaboration to ensure that the coal mine accidents are controlled as soon as possible. Local governments and coal mine enterprises are the main forces in the post-accident emergency management of coal mines, but the differences in their interest motives, preferences and cognitive structures make it difficult for the relevant emergency managers to make correct decisions in the complex accident management environment, therefore, the game relationship between conflict and cooperation among related subjects is explored based on the perspective of game theory. This study establishes a game model of coal mine accident response behavior between coal mining enterprises and local governments, and quantitatively adopts the method of numerical simulation analysis to conduct in-depth analysis of the influencing factors of their decision-making behavior. The results reveal that: 1) the establishment of an information sharing mechanism is an important condition for local governments to efficiently and quickly start the incident response process for coal mine accidents; 2) Under the proper supervision of local government, the impact of the reduction of emergency response cost on the active response of coal mining enterprises is more significant and direct, that is, The cost of emergency response is the decisive factor affecting the incident response work of coal mining company; 3) the establishment of emergency cost compensation mechanism and incentive mechanism should also be the focus of local governments in formulating emergency coordination policies in the future. This study provides scientifc and reasonable management suggestions in line with the actual situation of China and provides a useful reference for local government to formulate the optimal strategy for emergency coordination in coal mine emergencies, to improve the motivation of each coordinating subjects and to improve the current situation of emergency coordination in China's coal mines.

KEYWORDS

coal mine accident, emergency coordination, evolutionary game, simulation analysis, emergency management

1 Introduction

In a context where "peak-carbon-neutral" is increasingly becoming the new global political identity, From the European Union's push for a "Green New Deal" to the United States' return to the Paris Agreement (Rogelj et al., 2016), from Japan's establishment of a "Green Growth Plan" to South Korea's announcement of a carbon-neutral promotion strategy, the world's major economies are competing to make a "zero carbon commitment (Wang et al., 2022). China and the United S. are key players in driving the pace of global decarbonization (Xiang et al., 2022). As a key part of helping to achieve carbon neutrality goals, the global coal industry is also working to accelerate decarbonization.

As an unavoidable part of the process of decarbonization, it is important to study coal mine safety accident from management. Over the years, the level of emergency management in China has gradually improved, but the depth of coal mining caused by the deepening development of the coal mining industry has increased, and tailings depots are difficult to handle. This increases the risk coefficient of coal mine safety mining (Liu et al., 2019; Zhang et al., 2021), and the effective guarantee of the coal mine accident emergency system needs to be perfected urgently. There is an urgent need to improve the effectiveness of the coal mine accident emergency response system. Therefore, the regional coal mine emergency (CME) coordination mechanism established by the government, society and related coal mining enterprises is very important to improve the coal mine accident handling mechanism. At the same time, this study also intensifies the research on CME in order to inspire national designers or coal mining enterprises to implement management strategies.

The central, local government, coal mining enterprises and other relevant subjects are an important part of China's regional management and coordination system. The cooperation and coordination of these stakeholders can minimize unnecessary losses caused by CME by maximizing overall system function and enhancing emergency management capabilities (Hao et al., 2021). However, in the process of CME management and coordination, the different orientations and preferences of these stakeholders make complex conflicts of interest inevitable. Considering this situations, the author constructs a differential game model for the key stakeholders in the CME management coordination system (Hao et al., 2022). Then, it evaluated how different factors affected stakeholders' behavior and documented how various players behaved in the emergency synergy game. The study's findings offer crucial resources for conducting a quantitative analysis of CMA management coordinating practice. On this basis, in order to find the best way to improve CME management coordination and realize the smooth operation of regional CME management coordination mechanism, some measures to mobilize CME efficiency and improve management coordination efficiency are proposed.

2 Literature review

In the twenty meetings held recently in China, carbon neutrality is still one of the important issues, and reliable forecasts show that by 2060, 34.3%, 29.7% and 22.5% carbon reduction can be achieved in China, and it is urgent to create a number of enterprises with high emission reduction potential (Zhang et al., 2022). As an important part of the carbon emission reduction link, the post-processing of accidents and disasters in coal mining enterprises is a constant concern in the field of emergency management in China.

The post-processing of coal mine safety accidents requires the cooperation of three main actors: coal mining enterprises, local government and society, McMaster and Baber (2012) has verified the importance of achieving effective synergy among emergency response subjects, and Evers Mariele argued that coordination is an efficient way to cooperate (Evers et al., 2016).The studies of these scholars pointed us to the necessity of an effective model of cooperation between subjects in the post-processing of coal mine accidents. While the elements of regional emergency management procedures are an effective way to evaluate emergency management capabilities, an adequate supply of emergency funds is necessary for the continued and in-depth development of local government emergency cooperation, as well as for meeting public expectations and needs (Henstra, 2010). Therefore, the cost of emergency response in coal mine accident management is an important element that cannot be ignored.

An effective information sharing mechanism is necessary for local governments to respond quickly to coal mine accidents. For instance, The findings of research on enhancing China's urban rail transit's emergency response capacity from the perspective of inter-organizational coordination reveal that effective emergency response depends on the allocation and control of emergency organization, resources, planning, and information (Zhang et al., 2016). Additionally, Zhou and Reniers (2022) simulated how cooperation amongst emergency response bodies could increase the effectiveness of emergency response. As can be observed, the fundamental assurance for efficiently responding to emergencies is the capacity for coordination among the relevant parties. Based on the analysis of Katrina, Calixto and Larouvere (2010) indicated that there were major factors influencing the effectiveness of emergency response, such as different Standards and norms, public emergency response, and organizational advance links.

Apart from that, Ikeda et al. (1998) in the study of mine emergency coordination, learned the use of modern communication technologies for emergency rescue and developed an emergency rescue model. Yeo et al. (2017) indicated that the cooperative network of emergency response agencies is highly fragmented, with weak horizontal and vertical links (Schipper et al., 2015); Kinilakodi and Grayson (2011) introduced the reliability analysis method for the integrated management of mine safety emergencies in the prevention and control of coal mine safety accidents. Chen et al. (2022) analyzed the optimal channel selection strategy in mobile edge computing (MEC) emergency cooperative networks from the evolution of game theory perspective. And the scholars concerned in building game models and seeking stabilization strategies between enterprises and local governments and related subjects for the management of construction waste (Liu and Teng, 2022).Related to this, the idea of solving the equilibrium point of the game through system dynamics for the cost of construction waste disposal to explore the positive measures of stability among the stakeholders also inspired this paper very importantly (Liu et al., 2021). All of these modeling approaches have brought critical inspiration to the emergency response to coal mine safety accidents.

The development of an evolutionary game model of emergency coordination in Chinese coal mines needs to be based on the existing development of emergency management in China, where there are still some gaps that need to be noted. Through the analysis of these documents, we find that the study of CME management in China mainly focuses on the emergency plan, the management system, the management ability, the emergency rescue, and the problems and solutions of the emergency managers (Calixto and Larouvere, 2010). Many scholars have explored other issues, such as how to make contingency plan, how to resolve the problems in emergency plan, and how to design the emergency plan. Many researchers studied the problems in the preparation of the contingency plan in China and put forward that management coordination of CME needs deep and systematic research (He et al., 2019; Zhang and Xiang, 2020). However, there are only a few achievements in the field of emergency management, such as decision making, commodity flow, impact factors, assessment, *etc.* (Wang and Sheng, 2018). For example, Hu (2008) studied the importance of coordinating state and local coal mines and considered the need for a cooperation agreement. Liu et al. (2020) explained that it is necessary to establish a disaster rescue system among coal mines in different areas. Yang (2012) analyzed the *status quo* of the disaster relief and confirmed the effectiveness of the CME rescue team in CME rescue. Wang et al. (2017) analyzed the evolutionary game between subjects in CME management synergy based on the evolution of game the ory and the numerical simulation method. A number of scholars have explored the mechanism and capability of the coordination of emergency management of coal mines in China (Wang et al., 2012; Liang and Ning, 2014; Wang et al., 2014; Wang et al., 2016).

Existing research has important implications for this paper. China has only recently begun its investigation into the mechanism for emergency management synergy and has produced relatively few findings, especially those relevant to coal mines, according to an analysis of the current state of emergency management synergy in China and the international community. More research is needed on the emergency management synergy mechanis, there is still room for improvement in the research on how each subject's dynamic behavior evolves within the system. In addition, the coordination mechanism of emergency management needs further research, however, there are few studies on the dynamic behavior evolution of every member in the system. This also brings key insights to this research exploration. To this end, this paper introduces evolutionary game theory in the coordination mechanism of CME management, and explores the game model of local government and coal mining companies in the collaboration of coal mine disaster emergency response, and analyzes its impact through numerical simulation. Its goals are to direct the development of the regional CME system and enhance these subjects' capacity for emergency management synergy.

3 Model construction and solution

3.1 Analysis of game relationship between local government and coal mine enterprises

Due to the different cognitive structure, preference and interest motivation of each decision subject in coal mine accident emergency management, certain conflict is bound to occur in the decision-making action. Therefore, it can be considered that "conflict-free cooperative game" is the essence of the game relationship between coal mining enterprises and local governments, because coal mining enterprises and local governments have different social attributes. Because of its social attributes, local governments should not only safeguard regional public interests, but also safeguard the interests of organization members. However, in case of a conflict between the local government and the social public interest, some behaviors of leaders may cause damage to the social public interest because self-interest is the "natural" goal of the local government, that is, the government will have negative information integration behavior due to the high cost of integrating accident decision-making information. In the emergency disposal of coal mine accidents, coal mining enterprises, as the specific implementer, have sufficient resources with emergency information and technology, equipment and materials, emergency personnel, *etc.*, but they can also be regarded as profit making organizations to undertake social responsibility while maximizing its interests is its main goal because of their obvious nature of "economic man". When the social public interest coincides with the economic interest of coal mines, the government and coal mining enterprises will choose cooperation for the social public interest and positively respond. In case of a conflict of interest, especially when coal mining enterprises are required to invest more financial, material and human resources in the process of emergency disposal, resulting in the asymmetry of emergency response costs and economic revenues, they may cause damage to social and public interests due to self-interest, in other words, they will be not positive and choose negative measures in the face of coal mining accidents. In addition, when the regulatory capacity of the government and the functional departments can not be effectively brought into play, coal mining enterprises will also be likely to respond negatively.

Coal mining enterprises, as the main body of independent management, are responsible for their own profits and losses and pursue profits, so their own economic interests seriously restrict their subjective initiative in emergency response. Therefore, the emergency behavior strategies of coal mining enterprises set by the model can also be divided into two strategies: positive coordination and negative coordination. In the course of emergency response to coal mine accidents, the government should mainly adopt other financial or administrative penalties such as the removal of the main leading posts according to the performance and effectiveness of the emergency response process.

3.2 Model hypothesis and solution

In the emergency management of emergencies, the participating subjects of emergency decision-making are developing from a single regional government to a pluralistic organization, however, the different cognitive structures, preferences and interest motives of each decision-making subject are bound to produce certain contradictions and conflicts in the decision-making actions. Local governments are in a leading position in the emergency response to coal mine emergencies in China, playing the role of organization, coordination and control. Therefore, the government needs to collect, organize, and analyze a large amount of accident information to ensure the scientific formulation and implementation of emergency decisions. In the case of coal mine emergencies, coal mining enterprises become the most information unit at the accident site, and the main and most critical information source for the government is still coal mining enterprises, in addition to other ways to obtain information. Thus, the exploration of the information sharing mode between the government and coal mining enterprises is a very important part of the emergency decision-making information system for coal mining emergencies.

1) Model hypothesis

Assumption 1: Limited rationality. In the emergency game between coal mining enterprises and the local governments, both parties are limited rational participants, which means that the participants respond slowly in the face of information changes, inability to respond quickly and optimally to changes in information.

Assumption 2: Strategy space. Under the assumption of limited rationality, when sharing the decision-making information about the emergency management of coal mine accidents, due to the existence of incomplete accident information and interest differences in the game evolution process, the strategy space for local government agencies is (positive coordination, negative coordination). and the strategy space for coal mine enterprises will also (positive coordination, negative coordination). Therefore, there are two kinds of local government emergency behavior strategies in the model, it means that passive and positive coordination, among which the former includes punishing coal mining enterprises for poor disposal, setting up special emergency agencies, and announcing information release, while the latter refers to the low subjective initiative of local government in the process of coal mine accident emergency, lack of information communication and sharing with other emergency subjects, and failure to release emergency resource information serving coal mine accidents to the maximum extent.

Assumption 3: Gaming revenue. Combining the characteristics of emergency management in Chinese coal mines, this paper introduces reward and penalty mechanisms and makes assumptions about the game payoffs for both sides of the game.

Assuming that the cost of local government's positive coordination is C_1 (Including the supervision costs invested in actively integrating information and the operation and maintenance costs of information systems, *etc.*), the ability of information onversion is, Q_1 and the ability of information transformation adopting negative coordination and integration is $Q2$ ($Q1 > Q_2$), and the local government will impose a fine F on the coal mining enterprise if it finds that the coal mining enterprise is responding negatively in the process of the positive coordination and integration with the probability of discovery of N $(0 \le N \le 1)$. Assuming that the cost of positive response by coal mining enterprises is C_2, and the revenue it brings is R (the reputation of the enterprise and the political interests of the senior executives brought by positive response), the value of information positively sharing is V, and the concealment coefficient of negative information sharing is ρ $(0 \le \rho \le 1)$ (the concealment coefficient indicates the degree of concealment of accident information by coal mining enterprises, and the smaller the value, the more serious the concealment of information). If coal mining enterprises are found to information sharing positively, they will be rewarded W (positive incentives such as recognition and promotion from local governments).

Assumption 4: Behavioural strategy choice. Assume that the proportion of local governments involved in CME management that choose a positive synergistic strategy is x ($x \in [0, 1]$), then the proportion of departments that choose a negative synergistic strategy is (1-x). The proportion of decision makers in the coal mine enterprises involved that choose positive sharing is y ($y \in [0, 1]$), then the proportion of decision makers that choose negative sharing is (1-y).

According to the above hypotheses and analysis, the revenue matrix of local government and the coal mine enterprises in emergency management of coal mine sudden disasters is illustraed in Table 1.

According to the game revenue matrix of emergency coordination between local government and coal mining enterprises in Table 1, the expected revenue of local government when adopting positive integration and coordination is μ_{L1}, and the expected revenue when choosing negative coordination is μ_{L2}, with an average expected revenue of $\overline{\mu L}$, from which the expected revenue function of choosing positive coordination and negative coordination can be obtained as follows:

The expected revenue of local government when choosing positive coordination strategy is:

$$\mu L1 = y(VQ1 - C1) + (1 - y)(\rho VQ1 + NF - C1) \tag{1}$$

The expected revenue of local government when choosing negative coordination strategy is:

$$\mu L2 = y(VQ2) + (1 - y)(\rho VQ2) \tag{2}$$

Then the average expected revenue of the mixed strategy for local government agencies is:

$$\overline{\mu L} = x\mu L1 + (1 - x)\mu L2 \tag{3}$$

According to Malthusian equation (Akhmet et al., 2006), the replicator dynamics equation of local government is:

$$\begin{aligned} L(x) = \frac{dx}{dt} &= x(\mu L1 - \overline{\mu L}) = x(1 - x)(\mu L1 - \mu L2) \\ &= x(1 - x)\{[(1 - \rho)V(Q1 - Q2) - NF]y + \rho V(Q1 - Q2) + NF - C1\} \end{aligned} \tag{4}$$

In the same way, it is assumed that the expected revenue of coal mining enterprises is μ_{E1}, when adopting positive response strategies is μ_{E2}, when choosing negative response strategies, and the average expected revenue is $\overline{\mu E}$, from which:

When coal mining enterprises adopt positive response strategies, the revenue is as follows:

$$\mu E1 = x(W - C2 - V) + (1 - X)(R - C2 - V) = xW + R - C2 - V \tag{5}$$

When coal mining enterprises adopt negative response strategies, the revenue is as follows:

$$\mu E2 = x(-NF - \rho V) + (1 - X)(-\rho V) \tag{6}$$

Then, the average expected revenue of coal mine enterprises is

$$\overline{\mu E} = y\mu E1 + (1 - y)\mu E2 \tag{7}$$

Similarly, the replicator dynamics equation of coal mine enterprises is

$$\begin{aligned} E(y) = \frac{dy}{dt} &= y(\mu E2 - \overline{\mu E}) = y(1 - y)(\mu E1 - \mu E2) \\ &= y(1 - y)[(W + NF)x - (1 - \rho)V + R - C2] \end{aligned} \tag{8}$$

By combining formula (1) with (5), a two-dimensional replicator dynamics system of the game between local government organizations and coal mining enterprises in coal mine accident emergency coordination can be obtained. Let formula (4) and formula (8) equal to 0 respectively, namely:

TABLE 1 Revenue matrix of emergency cooperative game model between local government and coal mining enterprises.

		Coal mining enterprises	
		Positive response (y)	Negative response (1-y)
Local government	Positive coordination (x)	VQ_1-C_1, W-C_1-V	ρVQ_1+F-C_1 -NFρV
	Negative coordination (1-x)	VQ_2, R-C_2-V	ρVQ_2 -ρV

TABLE 2 detJ and trJ of equilibrium points of evolutionary game model between local government and coal mining enterprises.

Equilibrium points		Determinant and trace expression of Jacobian matrix
E1(0,0)	*detJ*	[ρV(Q1-Q2)+NF-C1]*[-(1-ρ)V + R-C2]
	trJ	[ρV(Q1-Q2)+NF-C1]+[-(1-ρ)V + R-C2]
E2(0,1)	*detJ*	-[V(Q1-Q2)-C1]*[-(1-ρ)V + R-C2]
	trJ	[V(Q1-Q2)-C1]-[-(1-ρ)V + R-C2]
E3(1,0)	*detJ*	-[ρV(Q1-Q2)+NF-C1]*[W + NF-(1-ρ)V + R-C2]
	trJ	[ρV(Q1-Q2)+NF-C1]+[W + NF-(1-ρ)V + R-C2]
E4(1,1)	*detJ*	[V(Q1-Q2)-C1]*[W + NF-(1-ρ)V + R-C2]
	trJ	-[V(Q1-Q2)-C1]-[W + NF-(1-ρ)V + R-C2]
E5(x*,y*)	*detJ*	{[C1- V(Q1-Q2)]*[-ρV(Q1-Q2)+NF-C1]*[W + NF-(1-ρ)V + R-C2]}/{ [(1-ρ)V(Q1-Q2)- NF]*(W + NF)}
	trJ	0

$$L(x) = x(1-x)\{[(1-\rho)V(Q1-Q2) - NF]y + \rho V(Q1-Q2) + NF - C1\} = 0 \; E(y) = y(1-y)[(W+NF)x - (1-\rho)V + R - C2] = 0 \quad (9)$$

The two-dimensional dynamic system has five equilibrium points, which are $E_1(0,0)$, $E_2(1,0)$, $E_3(0,1)$, $E_4(1,1)$ and $E_5(x^*, y^*)$.

Where, $x^* = \frac{(1-\rho)V+R-C2}{W+NF}$, $y^* = \frac{-\rho V(Q1-Q2)+C1-NF}{(1-\rho)V(Q1-Q2)-NF}$

4 Model analysis and result discussion

4.1 Stability analysis of equilibrium point

As mentioned above, the analysis of the local stability of a system with five equilibriums can be based on local stability of Jacobian matrix of the replicator dynamics system. The Jacobian matrix obtained by partial derivation of $L(x)$ and $E(y)$ is as follows:

$$J = \begin{pmatrix} \frac{dL(x)}{dx} & \frac{dL(x)}{dy} \\ \frac{dE(y)}{dx} & \frac{dE(y)}{dy} \end{pmatrix} = \begin{pmatrix} (1-2x)A & x(1-2x)B \\ y(1-y)C & (1-2y)D \end{pmatrix} \quad (10)$$

Where,
$A = \{[(1-\rho)V(Q1-Q2) - NF]y + \rho V(Q1-Q2) + NF - C1\}$;
$B = [(1-\rho)V(Q1-Q2) - NF]$; $C = (W + NF)$;
$D = [(W+NF)x - (1-\rho)V + R - C2]$.

Thus, *detJ* and *trJ* are respectively

$$detJ = (1-2x)(1-2y)AD - xy(1-x)(1-y)BC \quad (11)$$

TABLE 3 Evolutionary stability strategies of replicator dynamics systems with different parameters.

Equilibrium points	detJ	trJ	Local stability
E1(0,0)	>0	<0	ESS
E2(0,1)	>0	<0	ESS
E3(1,0)	>0	<0	ESS
E4(1,1)	>0	<0	ESS
E5(x*,y*)	>0	0	Unstable

$$trJ = (1-2x)A + (1-2y)D \quad (12)$$

The determinant *detJ* and trace *trJ* of the five equilibrium points are calculated respectively, as shown in Table 2.

Based on the trace of Jacobian matrix and the positive and negative sign of the determinant, we can get the local stability of the equilibrium point by using the local stability of the Jacobian matrix. By analyzing the relationship between different parameters, it can be concluded that there are four kinds of parameter cases with evolutionary stable strategies, as shown in Table 3. According to the analysis of determinant and trace expression of Jacobian matrix of five equilibriums, trace tr$J$ of $E_5(x^*, y^*)$ is 0, so it is unstable in the system evolution. Thus, the equilibriums of E_1(0,0), E_2(0,1), E_3(1,0) and E_4(1,1) are analyzed.

4.2 Result discussion

Based on the theory of evolutionary game, the stability strategies of evolutionary game in different scenarios are discussed:

Scenario 1: When $C_1 < V(Q_1 - Q_2)$, $(1-\rho)V + C_2 < W + NF + R$, it indicates that local government's emergency response cost is less than the value gain from the positive enhancement of the information transfer capability in emergency management, and when the sum of the revenues brought by coal mine enterprises' positive response, the rewards and fines brought by positive response is higher than the sum of the revenues brought by weakening the information density and the emergency response cost, the evolutionary game model evolutionary stability strategy (ESS) is (1,1), which means that E_4 (1,1) is in a game equilibrium state (ESS point) at this time, and (positive coordination and positive response) is the corresponding evolutionary stability strategy.

Scenario 2: When $C_1 > V(Q_1 - Q_2)$, $(1-\rho)V < R - C_2$, it indicates that in the emergency coordination of coal mine accidents, when the revenues brought by coal mine enterprises' weakening of information density are lower than the net revenues brought by their positive response or the losses brought by not fully controlling accidents are greater than the difference between the positive response and the passive response costs of handling accidents, especially as coal mine enterprises deepen their understanding of accident information or accident evolution, and predict that abnormal accidents may change, resulting in higher probability of serious accidents and increased economic losses, coal mine enterprises will choose to positively respond in order to prevent losses from expanding. However, local governments still choose a wait-and-see attitude because they do not know the accident status information, which may cause the emergency response cost to be greater than the revenue brought by the improvement of the ability to positively integrate information. According to the equilibrium condition, the revenue of coal mining enterprises choosing negative response is lower than that of choosing positive response, while revenue of local governments choosing negative coordination is higher than that of choosing positive coordination. The evolutionary game model ESS is (0,1), and at this time (negative coordination and positive response) is the corresponding evolutionary stable strategy.

Scenario 3: When $NF + \rho V(Q_1 - Q_2) > C_1$, $(1-\rho)V + C_2 > W + NF + R$, it indicates that the sum of the revenue from fines imposed by the government and the value revenue from positively improving the information transformation ability in the coal mine accident emergency coordination is higher than the positive coordination cost, and the sum of the revenue from concealing information and the emergency response cost of the coal mine enterprise is greater than the sum of the positive coordination revenue and the positive response incentives and the negative response fines, or the loss from not fully controlling the accident is less than the distinction between the optimistic coordination revenue and the passive coordination revenue. Judging from the equilibrium condition at this point, the income of the local government is higher than that of the negative coordination strategy, and the coal mining enterprise's revenue from choosing the positive response is less than that from choosing the negative response. At this time, the ESS of the evolutionary game model is (1,0), and (positive coordination, negative response) is the corresponding evolutionary stable strategy. Under the condition that the fines imposed by local governments and the cost of positive coordination remain unchanged, the government will tend to choose positive coordination because of the possible loss of credibility in negative coordination, which is determined by the probability that the government predicts that the accident will develop in a more serious direction. Therefore, coal mining enterprises must improve the transparency of their safety production information in order to more effectively enhance the probability of positive coordination of local governments. In this case, the local government will take an positive and cooperative strategy to participate in the accident disposal of coal mine enterprises, rather than wait for the support request of coal mine enterprises before they participate in the disposal of sudden accidents.

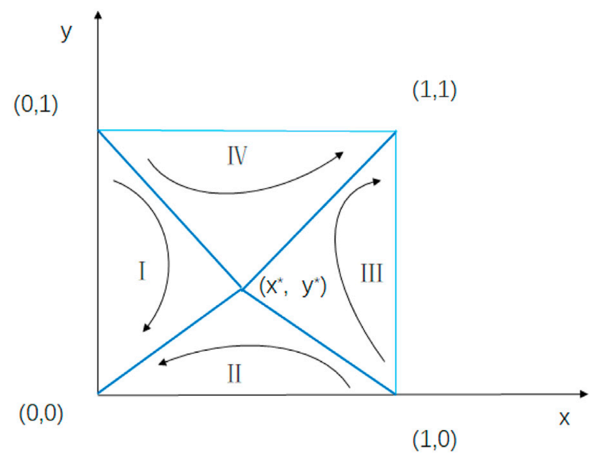

FIGURE 1
Dynamic path diagram of equilibrium point of evolutionary game model between the local government and coal mining enterprises.

Scenario 4: When $\rho V(Q_1 - Q_2) + NF < C_1$, $(1-\rho)V + C_2 > R$, it indicates that in the emergency coordination of coal mine accidents, if the emergency response cost of positive coordination by the government is higher than the sum of the revenues brought by the information transformation ability and the fines, and the sum of the revenues brought by the reduction of information density of coal mine enterprises and the costs of positive coordination is higher than the revenues brought by positive coordination, the ESS of the evolutionary game model is (0,0), and (negative coordination, negative response) is the corresponding evolutionary stable strategy.

Scenario 5: When $\rho V(Q_1 - Q_2) + NF < C_1 < V(Q_1 - Q_2)$, $R < (1-\rho)V + C_2 < W + NF + R$, it indicates that in the coordination emergency process of coal mine sudden disaster accident, if the sum of revenue and emergency response cost brought by concealing information is higher than the sum of positive coordination revenue and lower than the sum of positive coordination reward, positive coordination revenue and negative response penalty; when that positive emergency response cost of the local government in the accident emergency process is higher than the sum of the information conversion ability revenue and the enterprise fine revenue when the local government passively share information and lower than the revenue brought by the improvement of the information conversion ability when the coal mine positively shares information, the evolutionary stability strategy of the evolutionary game model is (1,1) and (0,0), and (x^*, y^*) is the

TABLE 4 Parameter assignment.

Symbols for quantities	Assignment	Symbols for quantities	Assignment
g_τ	0.5	η	0.5
k	0.8	μ	0.5
γ	6	ε_τ	0.5
C_1	7	ε_c	0.5
C_2	8	g_c	0.5
α	15	π	5
β	10	θ	4

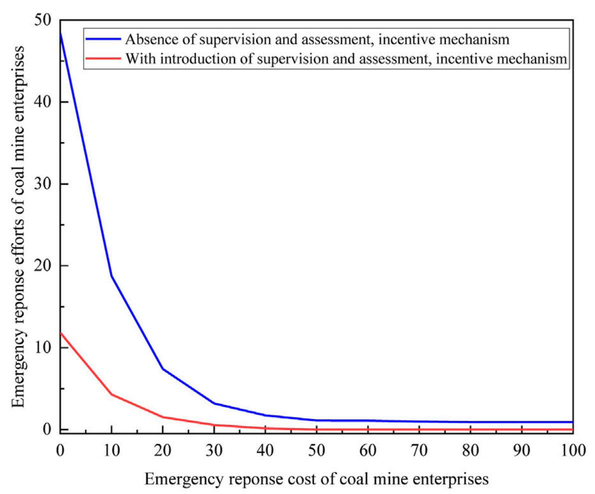

FIGURE 2
Relationship between emergency response efforts of coal mining enterprises and emergency response costs of local governments under the two scenarios.

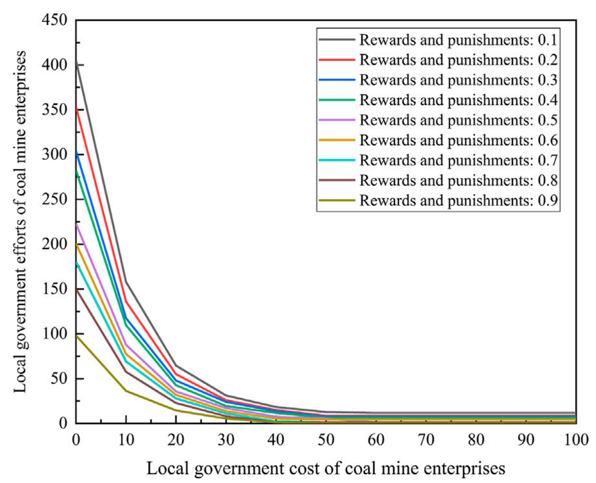

FIGURE 3
Relationship between emergency response efforts and emergency response costs of coal mine enterprises under different rewards and punishments.

saddle point, the initial state of the system will affect the final stability strategy, as depicted in Figure 1.

5 Numerical simulation

This study introduces Matlab simulation tool for numerical simulation analysis, so as to describe more clearly and intuitively the evolution of the emergency coordination game behavior between coal mining enterprises and local governments in coal mine accidents. Since it is difficult to obtain data related to emergency response in coal mine accidents, this paper determines the correlation coefficients based on relevant research results and existing constraints, such as $\alpha k \geq \theta$, $\beta k \geq \pi$, $2\alpha\gamma + \eta_\tau g_\tau \geq \theta\gamma/k$, $2\beta\gamma + \mu_c g_c \geq \pi\gamma/k$ *etc.* The parameter assignment reflects the relative relation of parameters. It is known that the benefit to the local government from the reduction in the loss of each coal mine accident includes the social benefit of the whole region.The unit loss factor for the local government caused by the mine accident comes from the whole area.Specific allocation is given in Table 4.

By using Matlab to simulate, we can get the relation between the level of emergency response and the cost under the two scenarios, it means that the introduction and lack of supervision and evaluation, incentive mechanism, as illustrated in Figure 2.

As illustrated in Figure 2. With the increase in the cost of emergency response, the level of emergency response effort will be decreased under the two cases where there is no monitoring and evaluation, and the level of emergency response is lower. Based on the trend of the curve, the level of emergency response will decrease rapidly with the increase of cost, which shows that the active participation of coal mining enterprises depends on the cost.

Under the assumption that the intensity of emergency rewards and penalties is 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8 and 0.9.Figure 3 shows the relationship between the emergency response and the cost of the coal industry. If the system of reward and penalty is fixed, as the cost of emergency response increases, the level of emergency response will gradually decrease, and the level of emergency response will also be raised.

Assuming that the intensity of the local government to the emergency rewards and punishments of coal mining enterprises is

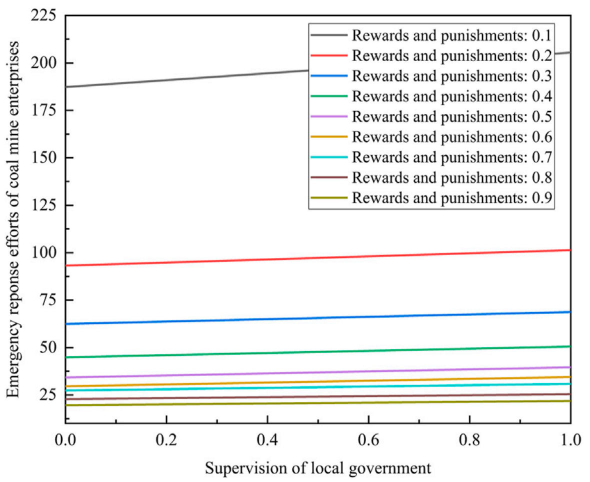

FIGURE 4
The relationship between emergency response efforts of coal mining enterprises and government supervision under different rewards and punishments.

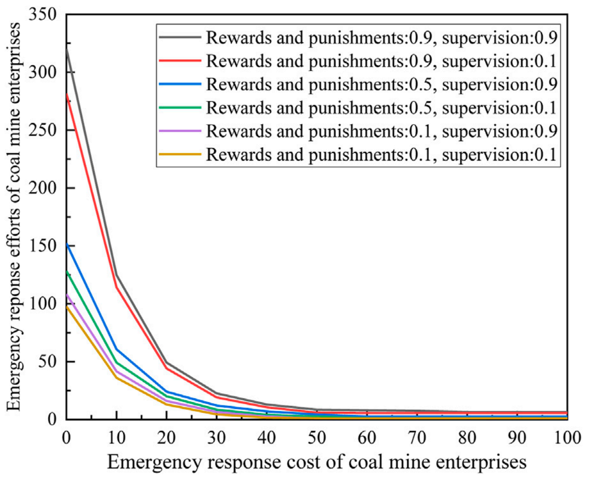

FIGURE 5
Relationship between emergency response efforts and costs of coal mining enterprises under different rewards and punishments.

0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9 respectively, Figure 4 describes the degree of emergency response efforts of coal mining enterprises with the change of the local government supervision. As ilustrated in the figure, If the local government's supervision is fixed, the degree of emergency response efforts of the coal mining enterprises will raise the improvement of emergency rewards and punishments, and the improvement of emergency response efforts of coal mining enterprises is more obvious after the rewards and punishments rise to 0.6; if the intensity of rewards and punishments is fixed, the level of emergency response efforts of coal mining enterprises will slowly increase with the improvement of local government supervision, indicating that the improvement of rewards and punishments is more conducive to enhancing the emergency response enthusiasm of coal mining enterprises than the government supervision.

Figure 5 shows the relationship between emergency response efforts and costs of coal mining enterprises when the local government's supervision on the coal mine enterprise is 0.9 and the rewards and punishments are 0.1, 0.5 and 0.9 respectively, and when the local government's supervision is 0.1 and the rewards and punishments are 0.1, 0.5 and 0.9 respectively. As shown in the figure, the curves under the three corresponding rewards and punishments intensity when the supervision intensity is 0.1 and 0.9 basically coincide, but the degree of coordination emergency effort decreases rapidly with the increase of emergency response cost, indicating that the influence of emergency response cost on the enthusiasm of coal mine enterprises is more immediate and significant than that of the emergency response is more direct and significant than that of emergency response cost. Therefore, in order to enhance the enthusiasm of coal mining enterprises in emergency response to sudden disasters and accidents, the local government should take measures to compensate for the emergency response costs of the enterprises to a greater extent, so that the economic interests of coal mining enterprises can be effectively protected and their initiative in emergency response can be higher.

6 Conclusion

Based on the evolutionary game theory, this study analyzes the problem of decision information sharing between the local government and the coal mining enterprises involved in the regional CME management synergy system. Through the analysis of the characteristics of emergency decision-making information of coal mining accidents and the game relationship between government and enterprises in emergency management of CME, a game model is established to obtain a two-dimensional replicated dynamical system of local government agencies and coal mining enterprises in emergency decision-making information of CME, and analyzes its and the stability conditions for each subject to reach the ideal state. Numerical simulations are also conducted by MATLAB tools to verify the feasibility and validity of the conclusions. As shown in Figure 1, the graph. is divided into four regions by saddle point (x^*, y^*), i.e., I-IV. When III and IV are the initial falling points of the system, the two-dimensional dynamic system converges at (1,1). Similarly, I and II are the initial falling points of the system, and the two-dimensional dynamic system converges at (0,0). On the basis of the above analysis, the following findings were obtained:

1) The necessary and sufficient conditions for the local government's evolutionary stabile strategy in coal mine accident emergency coordination are $C_1 < V(Q_1 - Q_2)$ or $\rho V(Q_1 - Q_2) + NF > C_1$, $y > y^* = [-\rho V(Q_1 - Q_2) + C_1 - NF]/[(1-\rho)V(Q_1 - Q_2) - NF]$, indicating that the local government will choose the evolutionary stable strategy of positive coordination when it has a low cost of coordination and emergency response, and will not change due to the strategy choice of coal mining enterprises. The main reason for the high cost of government emergency coordination may be the low information utilization and coordination efficiency in reality. Therefore, the local government should set up the coal mine accident emergency decision-making information coordination management department, and take it as the information driver to fast and effectively response to coal mine accidents. The establishment of an information sharing mechanism is an

important condition for local governments to efficiently and quickly start the emergency response process for coal mine accidents.

2) The necessary and sufficient conditions for the coal mine enterprises' evolutionary stabile strategy in coal mine accident emergency coordination are $(1-\rho)V + C_2 < R$ or $(1-\rho)V + C_2 < W + NF + R$, $x > x^* = [(1-\rho)V - R + C_2]/[W + NF]$, indicating that if the emergency task can be completed in the emergency process, the coal mine will reduce the emergency response cost to a certain extent. When the net benefit of the strategy chosen by the coal mine enterprise is large enough, the coal mine enterprise will choose to positively respond to this evolutionary stable strategy and will not change due to the local government strategic selection. The cost of emergency response is the decisive factor affecting the emergency response work of coal mining enterprises. In addition, the establishment of emergency cost compensation mechanism and incentive mechanism should also be the focus of local governments in formulating emergency coordination policies in the future.

3) The necessary and sufficient conditions for local governments and coal mining enterprises in coal mine emergency coordination are $C_1 < V(Q_1 - Q_2)$ or $\rho V(Q_1 - Q_2) + NF > C_1$ and $(1-\rho)V + C_2 < R$ or $(1-\rho)V + C_2 < W + NF + R$ when the evolutionary stabile strategy is (positive cooperation and positive response), indicating that the local governments and coal mining enterprises must improve mutual coordination in the emergency process of coal mine accidents, so that the coordination benefits can be improved and the game system stability strategy can exist for a long time.

This study explored the interests and conflicts between local governments and coal mining enterprises based on evolutionary game theory, which to a certain extent promotes the construction of emergency collaboration mechanism between coal mining enterprises and local governments, and the coal mining industry is a key link to achieve the goal of carbon neutrality, which has a certain demonstration radiation effect and provides a reference meaning for the collaboration between other industry sectors and local governments. For example, the analysis of the evolutionary game between the construction industry and local governments will be a research direction in the next stage.

China is in a critical period of social change, and the enhancement of governmental emergency synergy plays an important role in guaranteeing the creation of a stable and harmonious social environment. The research theme of this paper provides a breakthrough for the enhancement of the cooperation ability between local governments and other subjects, and is dedicated to providing practical and strategic suggestions for the comprehensive decision-making of local governments' emergency response ability. For example, the analysis of emergency synergy game between local government and other social subjects will also be included in the next stage of research.

Data availability statement

The original contributions presented in the study are included in the article. Further inquiries can be directed to the corresponding author.

Author contributions

PS, Conceptualization, methodology, validation. YH, writing-original draft preparation, data curation, editing. CS, supervision, editing. LZ, resources. All authors have read and agreed to the published version of the manuscript.

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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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References

Akhmet, M. U., Öktem, H. Ü. S., Pickl, S. W., and Weber, G. W. (2006). An anticipatory extension of Malthusian model. *AIP Conf. Proc.* 839, 1. doi:10.1063/1.2216034

Calixto, E., and Larouvere, E. L. (2010). The regional emergency plan requirement: Application of the best practices to the Brazilian case. *Saf. Sci.* 48, 991–999. doi:10.1016/j.ssci.2009.06.005

Chen, M., Liu, W., Wang, T., Zhang, S., and Liu, A. (2022). A game-based deep reinforcement learning approach for energy-efficient computation in MEC systems. *Knowl-Based Syst.* 235, 107660. doi:10.1016/j.knosys.2021.107660

Evers, M., Jonoski, A., Almoradie, A., and Lange, L. (2016). Collaborative decision making in sustainable flood risk management: A socio-technical approach and tools for participatory governance. *Environ. Sci. Policy.* 55, 335–344. doi:10.1016/j.envsci.2015.09.009

Hao, Y., Sun, C., Wei, J., and Gu, S. (2022). Study on measuring and evaluating the synergy effect of regional coal mine emergency management in China based on the composite system synergy model. *Geofluids* 1845795, 1–10. doi:10.1155/2022/1845795

Hao, Y., Sun, C., Wei, J., Gu, S., and Zhang, F. (2021). Differential game and simulation study on Management Synergy of Regional coal mine emergencies in China. *Shock Vib.* 4850651, 1–12. doi:10.1155/2021/4850651

He, Z., Wu, Q., Wen, L., and Fu, G. (2019). A process mining approach to improve emergency rescue processes of fatal gas explosion accidents in Chinese coal mines. *Saf. Sci.* 111, 154–166. doi:10.1016/j.ssci.2018.07.006

Henstra, D. (2010). Evaluating local Government Emergency Management Programs: What framework should public managers adopt? *Public admin. Rev.* 70, 236–246. doi:10.1111/j.1540-6210.2010.02130.x

Hu, S. T. (2008). Study on the joint transformation of local coal mine by large state-owned coal enterprises. *China coal.* 34, 18–20. doi:10.11731/j.issn.1673-193x.2018.09.028

Ikeda, Y., Beroggi, G. E. G., and Wallace, W. A. (1998). Supporting multi-group emergency management with Multimedia. *Saf. Sci.* 30, 223–234. doi:10.1016/s0925-7535(98)00038-1

Kinilakodi, H., and Grayson, R. L. (2011). Citation-related reliability analysis for a pilot sample of underground coal mines. *Accid. Anal. Prev.* 43, 1015–1021. doi:10.1016/j.aap.2010.11.033

Liang, Q. H., and Ning, Y. C. (2014). Research on mine safety emergency management synergy mechanism and countermeasures ability. *Coal Technol.* 2014, 64. doi:10.13301/j.cnki.ct.2014.12.064

Liu, J., and Teng, Y. (2022). Evolution game analysis on behavioral strategies of multiple stakeholders in construction waste resource industry chain. *Environ. Sci. Pollut. R.* 2022, 23470. doi:10.1007/s11356-022-23470-2

Liu, J., Yi, Y., Li, C. Z., Zhao, Y., and Xiao, Y. (2021). A model for analyzing compensation for the treatment costs of construction waste. *Sustain. Energy Techn.* 46, 101214. doi:10.1016/j.seta.2021.101214

Liu, Q., Meng, X., Li, X., and Luo, X. (2019). Risk precontrol continuum and risk gradient control in underground coal mining. *Process. Saf. Environ.* 129, 210–219. doi:10.1016/j.psep.2019.06.031

Liu, Y., Fan, Z., and Qi, H. (2020). Dynamic statistical evaluation of safety emergency management in coal enterprises based on neural network algorithms. *J. Intell. Fuzzy Syst.* 39, 5521–5534. doi:10.3233/jifs-189034

McMaster, R., and Baber, C. (2012). Multi-agency operations: Cooperation during flooding. *Appl. Ergon.* 43, 38–47. doi:10.1016/j.apergo.2011.03.006

Rogelj, J., Den Elzen, M., Höhne, N., Fransen, T., Fekete, H., Winkler, H., et al. (2016). Paris agreement climate proposals need a boost to keep warming well below 2 °C. *Nature* 534, 631–639. doi:10.1038/nature18307

Schipper, D., Gerrits, L., and Koppenjan, J. F. (2015). A dynamic network analysis of the information flows during the management of a railway disruption. *Eur. J. Transp. Infrast.* 15 (4). doi:10.18757/ejtir.2015.15.4.3091

Wang, D., Huangfu, Y., Dong, Z., and Dong, Y. (2022). Research hotspots and evolution trends of carbon neutrality—visual analysis of bibliometrics based on CiteSpace. *Sustainability* 14, 1078. doi:10.3390/su14031078

Wang, H. Q., Zhao, J., and Qi, H. L. (2016). Research based on collaborative regional coal mine emergency management system. *Coal Econ. Res.* 36, 66–69. doi:10.13202/j.cnki.cer.2017.12.014

Wang, J. F., Feng, L. J., and Zhai, X. Q. (2012). A system dynamics model of flooding emergency capability of coal mine. *Prz. Elektrotechniczn.* 88 (9), 209–211.

Wang, J. F., Chang, H. Y., Zhai, X. Q., and Feng, L. J. (2017). Analysis on evolution game and simulation of coal mine emergency cooperation. *Min. Saf. Environ. Prot.* 44 (4), 110–114.

Wang, J., and Sheng, L. (2018). Backtracking and prospect on emergency management research of coal mine enterprises in China—bibliometric analysis based on CiteSpace knowledge graph. *J. Saf. Sci.* 14 (9), 175–179.

Wang, L., Wang, Y., Cao, Q., Li, X., Li, J., and Wu, X. (2014). A framework for human error risk analysis of coal mine emergency evacuation in China. *J. Loss Prev. Proc.* 30, 113–123. doi:10.1016/j.jlp.2014.05.007

Xiang, X., Ma, M., Ma, X., Chen, L., Cai, W., Feng, W., et al. (2022). Historical decarbonization of global commercial building operations in the 21st century. *Appl. Energy* 322, 119401. doi:10.1016/j.apenergy.2022.119401

Yang, H. Y. (2012). Discussion on the merger of the mine rescue team and the fire station. *Coal Eng.* 1, 106–108.

Yeo, J., Comfort, K., and Yang, L. (2017). An expected event, but unprecedented damage. *Disaster Prev. Manag.* 26, 458–470. doi:10.1108/dpm-02-2017-0048

Zhang, J. G., and Xiang, X. J. (2020). The research on problems and suggestions in the preparation of emergency plan for coal mine accidents in China. *Coal Econ. Res.* 40, 70–93. doi:10.13202/j.cnki.cer.2020.02.012

Zhang, S., Ma, M., Xiang, X., Cai, W., Feng, W., and Ma, Z. (2022). Potential to decarbonize the commercial building operation of the top two emitters by 2060. *Resour. Conserv. Recy.* 185, 106481. doi:10.1016/j.resconrec.2022.106481

Zhang, X., Li, S., and Zhang, X. (2021). Evaluation of emergency rescue ability based on RS-IPA: Evidence from coal mining firms. *Nat. Hazards* 106, 1915–1929. doi:10.1007/s11069-021-04519-w

Zhang, Y., Zou, D., Zheng, J., Fang, X., and Luo, H. (2016). Formation mechanism of quick emergency response capability for urban rail transit: Inter-organizational collaboration perspective. *Adv. Mech. Eng.* 8 (6), 168781401664788. doi:10.1177/1687814016647881

Zhou, J., and Reniers, G. (2022). Petri-net based cooperation modeling and time analysis of emergency response in the context of domino effect prevention in process industries. *Reliab. Eng. Syst. Safe.* 223, 108505. doi:10.1016/j.ress.2022.108505