

Research Article

Game Modelling and Strategy Research on Trilateral Evolution for Coal-Mine Operational Safety Production System: A Simulation Approach

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In view of the particularity and high risk of coal mining industry, the decision-making behavior of multiple agents inside the coal-mine enterprise plays a very important role in ensuring the safety and sustainable development of coal mining industry. The existing literature studies on coal-mine safety production focus mainly on statically analyzing the game among the external entities such as the government, the enterprises themselves, and the employees inside the enterprise from a macro perspective, are short of research on revealing the dynamic interactions among the actors directly involved in the coal-mine accidents and also on proposals for effective interactions that will lead to improved safety outcomes. Therefore, this paper explores the use of evolutionary game theory to describe the interactions among the stakeholders in China's coal-mine safety production system, which includes the organization, the first-line miners, and the first-line managers. Moreover, the paper also explores dynamic simulations of the evolutionary game model to analyze the stability of stakeholder interactions and to identify equilibrium solutions. The simulation results show that when certain conditions are met, the decision-making behavior of the organization, miners, and managers can evolve into the unique ideal steady state (1, 1, 1). In addition, the strategy portfolio with a relatively high initial proportion of three agents converges more quickly to an ideal state than a relatively low strategy portfolio. Moreover, the stable state and equilibrium values are not affected by the initial value changes. Finally, we find that the combination of positive incentive policies and strict penalties policies can make the evolutionary game system converge to desired stability faster. The application of the evolutionary game and numerical simulation when simulating the multiplayer game process of coal-mine safety production is an effective way, which provides a more effective solution to the safety and sustainable development of coal mining industry.

1. Introduction

The Global Coal Market Report (2018–2023), jointly organized by the International Energy Agency (IEA) and the National Energy Group, points out that coal is still the core of the global energy system and global coal demand will remain stable in the next five years. The Coal Market Report 2017, jointly issued by the China Office of the Sustainable Cities and Communities (SUC) Project and the International Energy Agency (IEA), also points out that ensuring the economic benefits and ensuring the safety of coal industry are recent policy priorities. In order to ensure the

sustainable development of the coal industry, we must pay attention to the safety of the coal industry. Currently, while the safety performance of coal mines in China has improved overwhelmingly year after year [1, 2], coal-mine safety accidents are still frequent and the industry still has an appalling record of fatalities [3]. The losses caused by coal-mine safety accidents are catastrophic. Coal-mine safety accidents not only cause huge casualties but also cause huge economic losses and hinder the sustainable development of coal mining industry; meanwhile, they have a strong negative impact on social stability. Therefore, improving coal-mine safety production is the key to promoting the

sustainable development of coal mining industry and is one of the problems that China need to solve urgently.

In order to reduce the occurrence of coal-mine safety accidents, improve the current situation of coal-mine safety production, and ensure the sustainable development of coal mining industry, domestic and foreign scholars have studied effective countermeasures to promote coal-mine safety production from different perspectives and aspects.

The first research stream of coal-mine safety production enhancement focuses on the human factors such as controlling the unsafe behavior of miners. The unsafe behavior of miners is the most direct cause of coal-mine safety accidents and the main reason for destroying the normal operation of coal-mine safety production [4–6]. The miners always face a trade-off between work stress for safe operation and psychological benefits for unsafe operation, and reaching higher psychological and spiritual benefits might have strong substitution effects with safe operation. Therefore, alleviating the work stress response of miners and improving the safety behavior of them are the key to ensuring the normal operation of coal-mine safety production. At present, most scholars explore the generating mechanism of the unsafe behavior of miners, and results indicate that the individual characteristics (safety awareness, knowledge and skills, safety attitude, physical quality, and experience) of miners [7–9] and environmental factors [10–12] (working environment, equipment environment, social environment, family environment, etc.) have significant impact on the miners' behavioral decisions, which will in turn affect the safety production of coal mining enterprises.

The second research stream of coal-mine safety production enhancement focuses on the organizational factors [13–15]. The organization's investments in safety culture propaganda, safety training, safety regulations, and safety incentives will affect the level of the safety climate and thus affect the miners' behavioral decisions, ultimately affecting the safety production of coal mining enterprises. In short, the level of safety climate of organization plays an important role in the operation of coal-mine safety production, and the improvement level of safety climate depends on the organization's emphasis and the attention degree on safety [16, 17]. According to the theory of social exchange [18–20], the safety climate level of organization and the behavioral decision of miners are equivalent and reciprocal. At the same time, the supervision of first-line managers also affects the behavioral decision making of miners. And the behavioral decision-making model of miners [21] indicates that the expected total value of miners' unsafe behavior is determined by the decision weight function and the psychological value function, and the decision weight function is closely related to the supervision effect of supervisors. Before the miners make decisions, the supervision effect of supervisors will affect the miners' expectations of the task's interests; in the decision making, it influences the decision weight function and the psychological value function and then influences the behavior decision, which ultimately affects the safety production level of coal-mine enterprises. And some studies [22, 23] comprehensively analyzed human factors and organizational factors involved in mining accidents and

determined the relationships among these factors. The results showed that the human factors including skill-based errors, routine violations, and planned inappropriate operation and environmental factors had a higher relative importance in the accidents. Moreover, the environmental factors and human factors had a higher influence on unsafe acts.

The research streams of the previous two focus on the influencing mechanism of internal and external factors (individual characteristics, machinery and equipment, working environment, and organization management) on coal-mine safety production, and the "people-machine-ring-tube" causal system is gradually formed; to our knowledge, most of them analyze coal-mine safety production and its influencing factors from static and a single perspective and they are short of research on the interaction of various factors from the perspective of overall system, neglecting the subjective initiative of individual behavior.

In order to make up for the above defects, the third research stream of coal-mine safety production enhancement focuses on the gaming behaviors of stakeholders. The early game research studies [24–27] on coal-mine safety production mainly analyzed the relationship between the coal-mine regulators and coal enterprise and concluded that the coal enterprise's inadequate safety investment was the real cause of the frequent accidents and proposed that the penalty for the coal enterprise's unlawful production should be strengthened in the short term. These studies provide a promising foundation to explain the high incidence of coal accidents in China and improve the situation of coal-mine safety production. However, the above research studies mainly focus on statically analyzing the game between two stakeholders and neglect the dynamic process of game play. In order to explain the dynamic process of coal-mine safety production more systematically and comprehensively, Liu et al. [28] explored the use of evolutionary game theory to describe the long-term dynamic process of multiplayer game playing in coal-mine safety regulation under the condition of bounded rationality. Furthermore, the multiplayer evolutionary game was simulated by adopting system dynamics to analyze the implementation effect of different penalty strategies on the game process and game equilibrium. To promote the safety education level of China's coal mining enterprises, the government, coal mining enterprises, and employees are included in the evolutionary game model to explore the game relation and evolutionary path of the decision-making behavior among the three stakeholders in the safety management system [29, 30]. However, they focus mainly on analyzing the game between the external entities such as the government, the enterprises themselves, and the employees from a macro perspective, are short of research on revealing the dynamic interactions among the actors directly involved in the coal-mine accidents and also on proposals for effective interactions that will lead to improved safety outcomes. Although Yu et al. [31] constructed an evolutionary game model of workers' behavior in coal mining enterprises, only the static game between the two agents such as the managers and miners was considered. Actually, the stakeholders in coal-mine safety production

system include the organization, the first-line miners, and the first-line managers, and the operational system is the process in which these game agents interact with each other in complex environments [32–34]. In the process of coal-mine safety production, the players operate within bounded rationality, and their strategy selections are not always unchanged or static; instead, they change strategies dynamically by observing and comparing payoffs with others and adjusting their strategy selections, leading the evolutionary stable states in the game. Therefore, to help address this gap in the research, this paper explores the use of evolutionary game theory to describe the long-term dynamic process of multiplayer game playing in coal-mine safety production under the condition of bounded rationality. Furthermore, the multiplayer evolutionary game is simulated by adopting Matlab simulation technology to analyze its stability, and then effective stability control strategies are proposed and checked based on the simulation analysis including the set of stakeholders.

The remainder of this paper is organized as follows. Section 2 constructs a trilateral evolutionary game model of coal-mine safety production and analyzes the stability and balance of the game model. Section 3 presents the three-player evolutionary game simulation based on Matlab simulation technology and finds the best stable equilibrium point. Section 4 discusses the effectiveness of simulation results and internal driving strategy of coal-mine safety production. Finally, concluding remarks are presented in Section 5.

2. Trilateral Game Model of Coal-Mine Safety Production

Evolutionary game theory was developed to overcome the disadvantages of traditional game theory when analyzing the bounded rationality of players and the dynamic process of game playing [35–39]. In the process of coal-mine safety production in China, the players are bounded rational and they change their strategies dynamically by observing and comparing payoff with others and then adjust their strategies. Therefore, evolutionary game theory is more suitable for studying the long-term dynamic game of bounded rational players in China's coal-mine safety production system.

2.1. Game Design and Description. Currently, the work behavior of all employees in the coal-mine enterprise determines the status of coal-mine safety production. Here, the safety production system is defined relative to the safety supervision system. The current game system of coal-mine safety supervision is the game between the company's external regulators (including national regulators and local safety regulators) and the coal mining enterprises themselves; however, the safety production system refers to the game among the participants in the internal safety management system of coal-mine enterprise. The stakeholders in coal-mine safety production system include the organization, the first-line miners, and the first-line managers.

Among them, the organization refers to the senior managers of coal-mine enterprises, and their main duties include formulating reasonable reward, punishment measures, and safety management decisions; the first-line miners represent the employees who carry out front-line operations, whose unsafe behavior most directly leads to accidents; and the first-line managers are safety supervision departments, which mainly supervise the daily safety of coal miners. Therefore, the work behavior includes the senior regulation of the organization, the safe operation of the miners, and the grass-root supervision of the managers. The systemically evolutionary game of these stakeholders in the coal-mine safety production is developed and studied.

According to the Regulations of Coal Mining Safety Management, the organization is responsible for protecting coal enterprises' production situation by the incentive strategy. To represent their incentive strategy in the evolutionary game model, we designated x ($0 \leq x \leq 1$) as the incentive ratio of the organization. When $x=0$ or $x=1$, it represents general incentive or positive incentive. Furthermore, the decisions about the incentive strategy have cost implications. The positive incentive cost is high, so limited incentive level is practical. During the process of coal mining, r_1 represents the profits from positive incentive and c_1 represents the safety investment cost of positive incentive. If the organization chooses general incentive, it will save the safety investment cost but may increase the accident probability and then result in an expected loss later on, and the cost which organization adopts general incentive is c_2 , $c_1 < c_2$, and the profit is r_2 .

The miners choose y ($0 \leq y \leq 1$) as their strategy in their operation process, in which y represents safety operation ratio. When $y=0$ or $y=1$, it represents unsafe operation and safe operation, respectively. During the process of coal mining, t_1 represents the safety performance of safe operation, t_2 represents the safety rewards of safe operation under positive incentives, t_3 represents the safety rewards of safe operation under general incentives, and c_3 represents the safe operation cost. If the miners choose unsafe operation, it will save the cost and gain physical and mental benefits but may increase the accident probability and then result in an expected punishment loss later on. During this process, t_4 represents the physical and mental profits, t_5 represents the safety performance of unsafe operation, c_4 represents the unsafe operation cost, c_5 represents the fine when the unsafe behavior of miner are supervised and reported by the manager, and c_6 represents the bribe cost of miner paying to the manager.

The managers choose z ($0 \leq z \leq 1$) as their strategy when supervising the miners, in which z represents supervision ratio of the managers. When $z=0$, it represents the dereliction supervision duty and even power rent seeking, and $z=1$ represents strict execution of supervision duties. During the process of supervising, s_1 represents the partial "commission" profits from fines for their safety supervision work, s_3 represents the safety performance of safety supervision, s_5 represents the safety rewards of safety supervision under positive incentives, s_6 represents the safety rewards of safety supervision under general incentives, and

c_7 represents the safety supervision cost. If the managers choose dereliction of supervision duty and even power rent seeking, they will gain rents from miners but also undertake expected loss later at the same time. During this rent-seeking process, s_2 represents the "bribe" profits, s_4 represents the safety performance of rent seeking, $s_4 < s_3$, and c_7 represents the rent-seeking cost.

The above variables are shown in Table 1. Furthermore, the payoff matrix among the organization, miners, and managers is shown in Table 2 according to above preceding assumption and analysis.

2.2. Game Solution. According to the evolutionary game theory, replicator dynamics is used to represent the learning and evolution mechanism of individuals in the process of coal-mine safety production. Therefore, the organization's positive incentive fitness and general incentive fitness can be obtained as follows based on the above analysis and Table 2:

$$\begin{aligned} U_x &= z[y(r_1 - c_1) + (1 - y)(r_1 - c_2 + c_5 - s_1)] \\ &\quad + (1 - z)[y(r_1 - c_1) + (1 - y)(r_1 - c_1)] \quad (1) \\ &= yz(s_1 - s_5) + z(c_5 - s_1) + r_1 - c_1, \end{aligned}$$

$$\begin{aligned} U_{1-x} &= z[y(r_2 - c_2) + (1 - y)(r_2 - c_2 + c_5 - s_3 - s_1)] \\ &\quad + (1 - z)[y(r_2 - c_2) + (1 - y)(r_2 - c_2)] \quad (2) \\ &= yz(s_1 + s_3 - c_5) + z(c_5 - s_3 - s_1) + r_2 - c_2, \end{aligned}$$

where U_x represents positive incentive fitness and U_{1-x} represents general incentive fitness.

Thus, average fitness of the organization can be obtained as follows:

$$\bar{U}_{x,1-x} = xU_x + (1 - x)U_{1-x}. \quad (3)$$

According to the replicator dynamics, the change rate of x is as follows:

$$\begin{aligned} \frac{dx}{dt} &= x(U_x - \bar{U}_{x,1-x}) = x(U_x - (xU_x + (1 - x)U_{1-x})) \\ &= x(1 - x)(U_x - U_{1-x}). \end{aligned} \quad (4)$$

Let $F(x, y, z) = (dx/dt)$ and substitute equations (1) and (2) into equation (4) and then get equation (5) as follows, namely, organization's replicated dynamic equation:

$$\begin{aligned} F(x, y, z) &= x(1 - x)\{[yz(s_1 - s_5) + z(c_5 - s_1) + r_1 - c_1] \\ &\quad - [yz(s_1 + s_3 - c_5) + z(c_5 - s_3 - s_1) + r_2 - c_2]\}. \end{aligned} \quad (5)$$

Similarly, the change rate of y and z are as follows:

$$\begin{aligned} G(x, y, z) &= \frac{dy}{dt} = y(U_y - U_{1-y}) = y(1 - y)[xz(t_2 - t_3) \\ &\quad + z(t_3 - t_5 + t_1 + c_5 - c_6) - c_3 - t_4 + c_4 + c_6], \\ H(x, y, z) &= \frac{dz}{dt} = z(U_z - U_{1-z}) = z(1 - z)[xy(s_5 - s_6) \\ &\quad + y(s_6 - s_1 - s_3 + s_4 + s_2 - c_7) \\ &\quad + s_1 + s_3 - s_2 - s_4]. \end{aligned} \quad (6)$$

In conclusion, the population dynamic of the evolutionary game in the coal mining safety production can be represented by the following replicated dynamic equation set:

$$\begin{cases} F(x, y, z) = \frac{dx}{dt} = x(U_x - U_{1-x}) = x(1 - x)(-yzs_3 + zs_3 + r_1 - c_1 - r_2 + c_2), \\ G(x, y, z) = \frac{dy}{dt} = y(U_y - U_{1-y}) = y(1 - y)[xz(t_2 - t_3) + z(t_3 - t_5 + t_1 + c_5 - c_6) - c_3 - t_4 + c_4 + c_6], \\ H(x, y, z) = \frac{dz}{dt} = z(U_z - U_{1-z}) = z(1 - z)[xy(s_5 - s_6) + y(s_6 - s_1 - s_3 + s_4 + s_2 - c_7) + s_1 + s_3 - s_2 - s_4]. \end{cases} \quad (7)$$

The above replicated dynamic equation set equation (7) reflects the speed and direction of the strategy adjustment among the organization, miners, and managers. When it is equal to zero, it shows that the speed of strategy adjustment is equal to zero and the evolutionary game system reaches a relatively stable equilibrium state. Furthermore, the stability of equilibrium solution can be obtained by analyzing the Jacobian matrix's determinant [40–43] and trace of the

game, which reflects the existence of the evolutionary stable strategy.

2.3. Stability Analysis of the Evolutionary Game Model. According to the replication dynamic equations of the organization, miners, and managers, the eight equilibrium points of the dynamic games are $E_1(0, 0, 0)$, $E_2(0, 0, 1)$, $E_3(0,$

TABLE 1: Variables in the game among the organization, miners, and managers.

Variables	Meaning of the variables	Notes
x	Incentive ratio	$0 \leq x \leq 1$
y	Safe operation ratio	$0 \leq y \leq 1$
z	Safety supervision ratio	$0 \leq z \leq 1$
r_1	Positive incentive profits of organization	$r_1 > 0$
c_1	Positive incentive cost of organization	$c_1 > c_2$
r_2	General incentive profits of organization	$r_2 > 0$
c_2	General incentive cost of organization	$c_2 > 0$
t_1	Safety performance of safe operation of miners	$t_1 > t_5$
t_2	Safety rewards of safe operation of miners under positive incentives	$t_2 > t_3$
t_3	Safety rewards of safe operation of miners under general incentives	$t_3 > 0$
c_3	Safe operation cost of miners	$c_3 > 0$
t_4	Physical and mental profits of unsafe operation of miners	$t_4 > 0$
t_5	Safety performance of unsafe operation of miners	$t_5 > 0$
c_4	Unsafe operation cost of miners	$c_4 > 0$
c_5	The fine of unsafe operation of miners	$c_5 > 0$
c_6	The bribe cost of miner paying to the manager	$c_6 > 0$
s_1	The "commission" profits from fines for manager's safety supervision	$s_1 > 0$
s_3	Safety performance of safety supervision of managers	$s_3 > s_4$
s_5	Safety rewards of safety supervision of managers under positive incentives	$s_5 > s_6$
s_6	Safety rewards of safety supervision of managers under general incentives	$s_6 > 0$
c_7	Safety supervision cost or rent-seeking cost of managers	$c_7 > 0$
s_2	The "bribe" profits of managers	$s_2 > 0$
s_4	Safety performance of rent-seeking of managers	$s_4 > 0$

$1, 0), E_4(0, 1, 1), E_5(1, 0, 0), E_6(1, 0, 1), E_7(1, 1, 0),$ and $E_8(1, 1, 1)$, respectively. The Jacobian matrix of the dynamic game of the organization, miners, and managers is shown in the following equation:

$$\begin{aligned}
 J &= \begin{pmatrix} \frac{\partial F(x, y, z)}{\partial x} & \frac{\partial F(x, y, z)}{\partial y} & \frac{\partial F(x, y, z)}{\partial z} \\ \frac{\partial G(x, y, z)}{\partial x} & \frac{\partial G(x, y, z)}{\partial y} & \frac{\partial G(x, y, z)}{\partial z} \\ \frac{\partial H(x, y, z)}{\partial x} & \frac{\partial H(x, y, z)}{\partial y} & \frac{\partial H(x, y, z)}{\partial z} \end{pmatrix} \quad (8) \\
 &= \begin{pmatrix} B_1 & B_2 & B_3 \\ B_4 & B_5 & B_6 \\ B_7 & B_8 & B_9 \end{pmatrix},
 \end{aligned}$$

where

$$\begin{aligned}
 B_1 &= (1 - 2x)(-yzs_3 + zs_3 + r_1 - c_1 - r_2 + c_2); \\
 B_2 &= -xz(1 - x)s_3; \\
 B_3 &= x(1 - x)(1 - y)s_3; \\
 B_4 &= yz(1 - y)(t_2 - t_3); \\
 B_5 &= (1 - 2y)[xz(t_2 - t_3) + z(t_3 - t_5 + t_1 + c_5 - c_6) \\
 &\quad - c_3 - t_4 + c_4 + c_6]; \\
 B_6 &= y(1 - y)[x(t_2 - t_3) + t_3 - t_5 + t_1 + c_5 - c_6]; \\
 B_7 &= yz(1 - z)(s_5 - s_6); \\
 B_8 &= z(1 - z)[x(s_5 - s_6) + s_6 - s_1 - s_3 + s_4 + s_2 - c_7]; \\
 B_9 &= (1 - 2z)[xy(s_5 - s_6) + y(s_6 - s_1 - s_3 + s_4 + s_2 - c_7) \\
 &\quad + s_1 + s_3 - s_2 - s_4]. \quad (9)
 \end{aligned}$$

From the local stability of the Jacobian matrix, it can be seen that when the equilibrium point is brought into the matrix J to satisfy both the determinant $\text{Det}_J > 0$ and the trace $\text{Tr}_J > 0$, the equilibrium point is an evolutionary stability strategy, and the decision-making agent reaches the evolutionary stability strategy (ESS); if the determinant $\text{Det}_J > 0$ and the trace $\text{Tr}_J > 0$, the equilibrium point is unstable; if the determinant $\text{Det}_J < 0$ and the trace $\text{Tr}_J = 0$ or is indeterminate, the equilibrium point is a saddle point. The stability analysis results of the above eight equilibrium points are as follows:

- (1) The condition that the equilibrium point $E_1(0, 0, 0)$ is satisfied as the stable equilibrium point is $r_1 - c_1 - r_2 + c_2 < 0, c_3 + t_4 - c_4 - c_6 < 0, s_1 + s_3 - s_2 - s_4 < 0$. Under this condition, we find that the unsafe operation cost of miners is greater than the profits of the unsafe operation. Obviously, the miners will change their initial strategy, which contradicts the equilibrium point. So, the equilibrium point $E_1(0, 0, 0)$ is not an evolutionary stability strategy.
- (2) The condition that the equilibrium point $E_2(0, 0, 1)$ is satisfied as the stable equilibrium point is $s_3 + r_1 - c_1 - r_2 + c_2 < 0, t_1 + t_3 - t_4 - t_5 + c_4 + c_5 - c_3 < 0, s_2 + s_4 - s_1 - s_3 < 0$. Under this condition, we find that the profits of safety supervision of managers are less than the profits of rent seeking. Obviously, the managers will choose power rent-seeking strategies, which contradicts the equilibrium points, so the equilibrium point $E_2(0, 0, 1)$ is not an evolutionary stabilization strategy.
- (3) The condition that the equilibrium point $E_3(0, 1, 0)$ is satisfied as the stable equilibrium point is $r_1 - c_1 - r_2 + c_2 < 0, c_3 + t_4 - c_4 - c_6 < 0, s_6 - c_7 < 0$. However, this condition of $s_6 - c_7 < 0$ cannot judge the relationship between the safety regulation cost and the profits, so the equilibrium point $E_3(0, 1, 0)$ is not an evolutionary stabilization strategy.

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

		Miner			
		Safe operation	Unsafe operation		
Organization	Positive incentive	$r_1 - c_1$	$r_1 - c_1 + c_5 - s_1$	Manager	
		$t_1 + t_2 - c_3$	$t_4 + t_5 - c_4 - c_5$		
	General incentive	$s_3 + s_5 - c_7$	$s_1 + s_3 - c_7$		Safety supervision
		$r_2 - c_2$	$r_2 - c_2 + c_5 - s_3 - s_1$		
	Positive incentive	$t_1 + t_3 - c_3$	$t_4 + t_5 - c_4 - c_5$		No supervision or even power rent seeking
		$s_3 + s_6 - c_7$	$s_1 + s_3 - c_7$		
General incentive	$r_1 - c_1$	$r_1 - c_1$			
	$t_1 - c_3$	$t_1 + t_4 - c_4 - c_6$			
Positive incentive	s_3	$s_2 + s_4 - c_7$			
	$r_2 - c_2$	$r_2 - c_2$			
General incentive	$t_1 - c_3$	$t_1 + t_4 - c_4 - c_6$			
	s_3	$s_2 + s_4 - c_7$			

- (4) The condition that the equilibrium point $E_4(0, 1, 1)$ is satisfied as the stable equilibrium point is $r_1 - c_1 - r_2 + c_2 < 0$, $t_4 + t_5 - t_1 - t_3 - c_4 - c_5 + c_3 < 0$, $c_7 - s_6 < 0$. Under this condition, the net profits of organization's positive incentive are less than the net profits of the general incentive, so the organization will adopt the general incentive strategy; the net profits of the miners' unsafe operation are less than the net profits of safe operation, so the miner will take safe operation; the incentives for safety supervision are greater than the costs, so the managers will choose safety supervision strategy. Therefore, if the conditions of the evolutionary stability strategy are satisfied, the evolutionary stability strategy of the organization, miners, and managers will eventually evolve into {general incentive, safe operation, and safety supervision}, which indicates that the equilibrium point $E_4(0, 1, 1)$ is an evolutionary stabilization strategy.
- (5) The condition that the equilibrium point $E_5(1, 0, 0)$ is satisfied as the stable equilibrium point is $c_1 - r_1 + r_2 - c_2 < 0$, $c_3 + t_4 - c_4 - c_6 < 0$, $s_1 + s_3 - s_2 - s_4 < 0$. Under this condition, we find that the unsafe operation cost of miners is greater than the profits of the unsafe operation. Obviously, the miners will change their initial strategy, which contradicts the equilibrium point, so the equilibrium point $E_5(1, 0, 0)$ is not an evolutionary stability strategy.
- (6) The condition that the equilibrium point $E_6(1, 0, 1)$ is satisfied as the stable equilibrium point is $c_1 - r_1 + r_2 - c_2 - s_3 < 0$, $t_1 + t_2 - c_3 - t_4 - t_5 + c_4 + c_5 < 0$, $s_2 + s_4 - s_1 - s_3 < 0$. Under this condition, we find that the profits of safety supervision of managers are less than the profits of rent-seeking. Obviously, the managers will choose power rent-seeking strategies, which contradicts the equilibrium points, so the equilibrium point $E_6(1, 0, 1)$ is not an evolutionary stabilization strategy.
- (7) The condition that the equilibrium point $E_7(1, 1, 0)$ is satisfied as the stable equilibrium point is

$c_1 - r_1 + r_2 - c_2 < 0$, $c_3 + t_4 - c_4 - c_6 < 0$, $s_5 - c_7 < 0$. Under this condition, the net profits of organization's positive incentive are greater than the net profits of the general incentive, so the organization will adopt the positive incentive strategy; the net profits of the unsafe operation are less than the net profits of safe operation, so the miner will take safe operation; the safety supervision cost of managers is greater than the profits, so the managers will choose no supervision strategy or even rent-seeking strategy. Therefore, if the conditions of the evolutionary stability strategy are satisfied, the evolutionary stability strategy of the organization, miners, and managers will eventually evolve into {positive incentive, safe operation, and no supervision or even rent-seeking strategy}, which indicates that the equilibrium point $E_7(1, 1, 0)$ is an evolutionary stabilization strategy.

- (8) The condition that the equilibrium point $E_8(1, 1, 1)$ is satisfied as the stable equilibrium point is $c_1 - r_1 + r_2 - c_2 < 0$, $t_4 + t_5 - t_1 - t_2 - c_4 - c_5 + c_3 < 0$, $c_7 - s_5 < 0$. Under this condition, the net profits of organization's positive incentive are greater than the net profits of the general incentive, so the organization will adopt the positive incentive strategy; the net profits of the unsafe operation are less than the net profits of safe operation, so the miner will take safe operation; the safety supervision cost of managers is less than the profits, so the managers will choose safety supervision. Therefore, if the conditions of the evolutionary stability strategy are satisfied, the evolutionary stability strategy of the organization, miners, and managers will eventually evolve into {positive incentive, safe operation, and safety supervision}, which indicates that the equilibrium point $E_8(1, 1, 1)$ is an evolutionary stabilization strategy.

From the stability analysis of the eight equilibrium points, we find that $E_4(0, 1, 1)$, $E_7(1, 1, 0)$, and $E_8(1, 1, 1)$ are evolutionary stability strategies of the organization, miners, and managers.

3. Simulation Analysis of the Evolutionary Game Model

Matlab simulation technology is an effective computer simulation method for studying feedback behavior in complex systems [44–49]. In the above multiplayer game, the individuals constantly imitate and learn from other individuals by observing and comparing the payoffs with others and then adjust their strategy selection, which constitutes the feedback behavior in the group. Therefore, this section will first use the Matlab simulation technology to verify the above three equilibrium points and then provide an effective simulation platform to determine reasonable regulation strategies.

3.1. Numerical Simulations of the Stable Equilibrium Point. In order to more intuitively show the evolution path of the system, the above evolutionary game equilibrium points are analyzed and verified by numerical simulation.

In order to make the system finally evolve to the ideal state point $E_4(0, 1, 1)$, the initial values of each parameter need to meet the following conditions: $r_1 - c_1 - r_2 + c_2 < 0$, $t_4 + t_5 - t_1 - t_3 - c_4 - c_5 + c_3 < 0$, and $c_7 - s_6 < 0$, and the initial values are set as $c_1 = 15$, $r_1 = 15$, $c_2 = 11$, $r_2 = 13$, $s_3 = 2$, $t_1 = 3$, $t_2 = 3$, $t_3 = 2$, $t_4 = 6$, $t_5 = 1$, $c_3 = 4$, $c_4 = 3$, $c_5 = 4$, $c_6 = 3$, $s_1 = 3$, $s_2 = 3$, $s_4 = 1$, $s_5 = 7$, $s_6 = 6$, and $c_7 = 5$.

Under the above conditions, the initial value of x is fixed, and the initial values of y and z are randomly selected to verify the influence of the initial values of y and z on the change of x with time. Taking $x = 0.5$ as an example, the evolution curve of x is as shown in Figure 1(a). It can be seen from Figure 1(a) that the difference of the initial values of y and z affect the convergence speed of x , but x still monotonically decreases and converges to 0, indicating that the proportion of the organization selecting the “positive incentive” strategy will continue to decrease over time and ultimately all will choose the “general incentive” strategy regardless of the initial values of y and z . Taking $z = 0.5$ as an example, the values of x and y are varied to obtain the evolution curve of z , as shown in Figure 1(c). As can be seen in Figure 1(c), the difference of the initial values of x and y affect the convergence speed of z , but z still monotonically increases and converges to 1, indicating that the proportion of managers choosing “safety supervision” strategy will continue to increase over time and ultimately all will choose the “safety supervision” strategy regardless of the initial values of x and y . Taking $y = 0.5$ as an example, the values of x and z are varied to obtain the evolution curve of y , as shown in Figure 1(b). However, when the initial proportion of the organization adopting the “positive incentive” strategy and the managers adopting the “safety supervision” strategy is greater than 0.7, the miners will finally choose the safe operation; otherwise, the miners will eventually choose the unsafe operation, which is inconsistent with the stability of the equilibrium point $E_4(0, 1, 1)$. Therefore, the equilibrium point $E_4(0, 1, 1)$ is not an ideal steady state.

In order to make the system finally evolve to the ideal state point $E_7(1, 1, 0)$, the initial values of each parameter need to meet the following conditions: $c_1 - r_1 + r_2 - c_2 < 0$,

$c_3 + t_4 - c_4 - c_6 < 0$, and $s_5 - c_7 < 0$, and the initial values are set as $c_1 = 3$, $r_1 = 4$, $c_2 = 2$, $r_2 = 2$, $s_3 = 4$, $t_1 = 2$, $t_2 = 2$, $t_3 = 1$, $t_4 = 3$, $t_5 = 1$, $c_3 = 4$, $c_4 = 3$, $c_5 = 6$, $c_6 = 5$, $s_4 = 3$, $s_5 = 2$, $s_6 = 1$, and $c_7 = 3$.

Similarly, under the above conditions, the evolution curves of x , y , and z are shown in Figures 2(a)–2(c), respectively. It can be seen from Figure 2(a) that the difference of the initial values of y and z affect the convergence speed of x , but x still monotonically increases and converges to 1, indicating that the proportion of the organization selecting the “positive incentive” strategy will continue to increase over time and ultimately all will choose the “positive incentive” strategy regardless of the initial values of y and z . It can be seen from Figure 2(b) that the difference of the initial values of x and z has an effect on the convergence speed of y , but y still monotonically increases and converges to 1, indicating that the proportion of miners choosing the “safe operation” strategy will continue to increase over time and eventually all choose the “safe operation” strategy regardless of the initial values of x and z . As shown in Figure 2(c), however, it is found that managers will abandon safety supervision when the initial probability of the organization adopting “positive incentive” strategy and the miners adopting “safe operation” strategy is large, while the managers will choose safety regulation when the initial probability of the organization adopting “positive incentive” strategy and the miners adopting “safe operation” strategy is small, which is inconsistent with the stability of the equilibrium point $E_7(1, 1, 0)$. Therefore, the equilibrium point $E_7(1, 1, 0)$ is not an ideal steady state.

In order to make the system finally evolve to the ideal state point $E_8(1, 1, 1)$, the initial values of each parameter need to meet the following conditions: $c_1 - r_1 + r_2 - c_2 < 0$, $t_4 + t_5 - t_1 - t_2 - c_4 - c_5 + c_3 < 0$, and $c_7 - s_5 < 0$, and the initial values are set as $c_1 = 18$, $r_1 = 20$, $c_2 = 17$, $r_2 = 18$, $s_3 = 6$, $t_1 = 3$, $t_2 = 3$, $t_3 = 2$, $t_4 = 4$, $t_5 = 2$, $c_3 = 6$, $c_4 = 4$, $c_5 = 7$, $c_6 = 6$, $s_1 = 3$, $s_2 = 3$, $s_4 = 1$, $s_5 = 6$, $s_6 = 5$, and $c_7 = 5$.

Similarly, under the above conditions, the evolution curves of x , y , and z are shown in Figures 3(a)–3(c), respectively. It can be seen from Figure 3(a) that the difference of the initial values of y and z affects the convergence speed of x , but x still monotonically increases and converges to 1, indicating that the proportion of the organization selecting “positive incentive” strategy will continue to increase over time and ultimately all will choose the “positive incentive” strategy. It can be seen from Figure 3(b) that the difference of the initial values of x and z has an effect on the convergence speed of y , but y still monotonically increases and converges to 1, indicating that the proportion of miners choosing the “safe operation” strategy will continue to increase over time and eventually all will choose the “safe operation” strategy. As can be seen in Figure 3(c), the difference of the initial values of x and y affects the convergence speed of z , but z still monotonically increases and converges to 1, indicating that the proportion of managers choosing “safety supervision” strategy will continue to increase over time and eventually all will choose the “safety supervision” strategy. This is consistent with the stability of the equilibrium point $E_8(1, 1, 1)$,

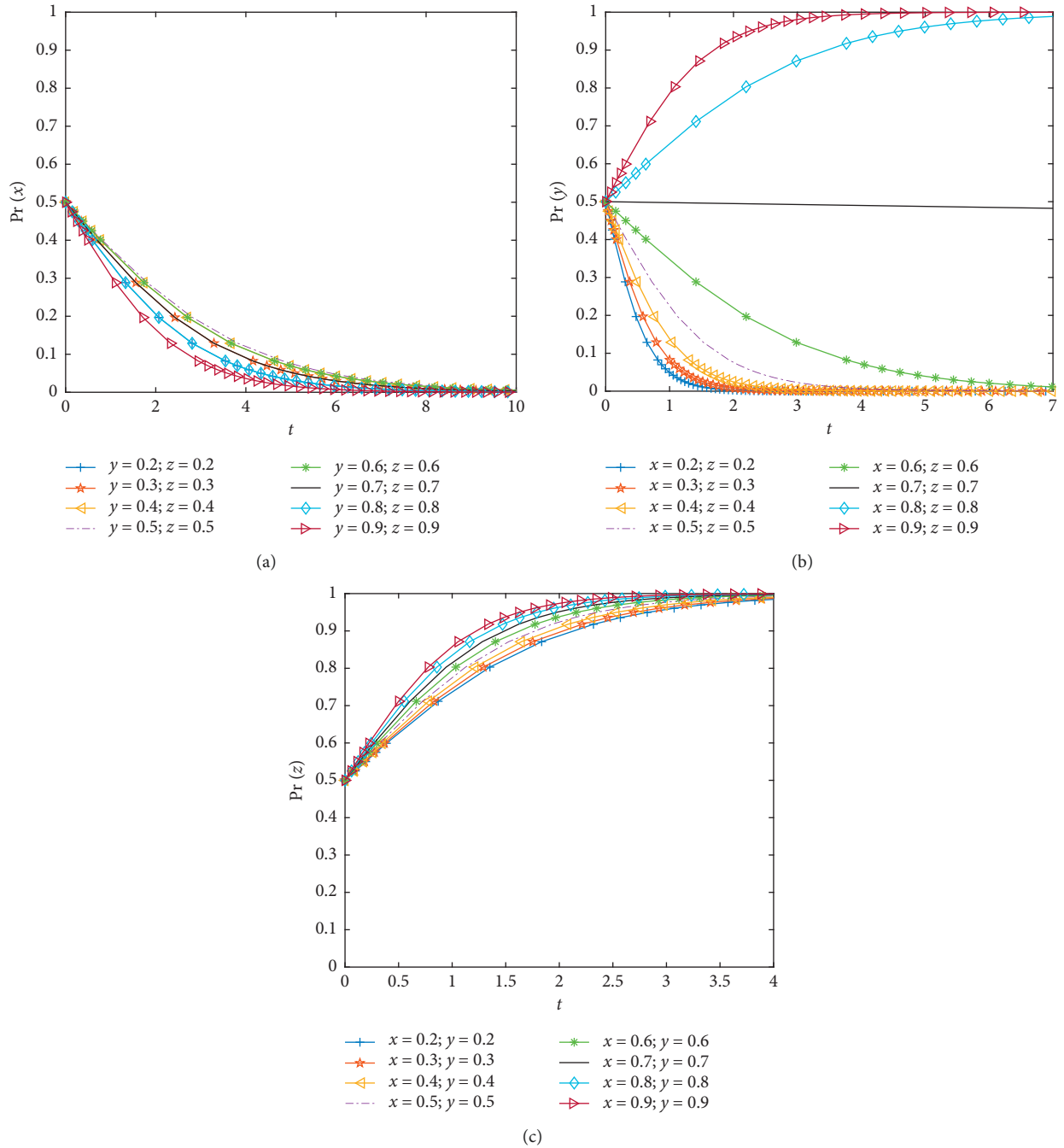


FIGURE 1: (a) Evolution curve of x when y and z change. (b) Evolution curve of y when x and z change. (c) Evolution curve of z when x and y change.

so the equilibrium point $E_8(1, 1, 1)$ is the unique ideal steady state.

It can be seen from Figure 3 that when the initial proportion of a game agent is determined, the change of the initial proportion of the other two agents has no effect on its final strategy choice. In order to more accurately describe the mutual influence of the three-party game, the initial proportion of the organization is set to $x = 0.4$, the initial proportion of the miners is set to $y = 0.5$, and the initial proportion of the managers is set to $z = 0.6$, and the

evolution curves of x , y , and z are shown in Figures 4(a)–4(c), respectively.

As shown in Figure 4, when the net profits of organization's positive incentive are greater than the net profits of the general incentive, the net profits of the unsafe operation are less than the net profits of safe operation, and the safety supervision cost of managers is less than the profits; regardless of the initial proportion of x , y , and z , the three agents will choose the optimal and initial decision, and the greater the initial proportion, the shorter the time to reach

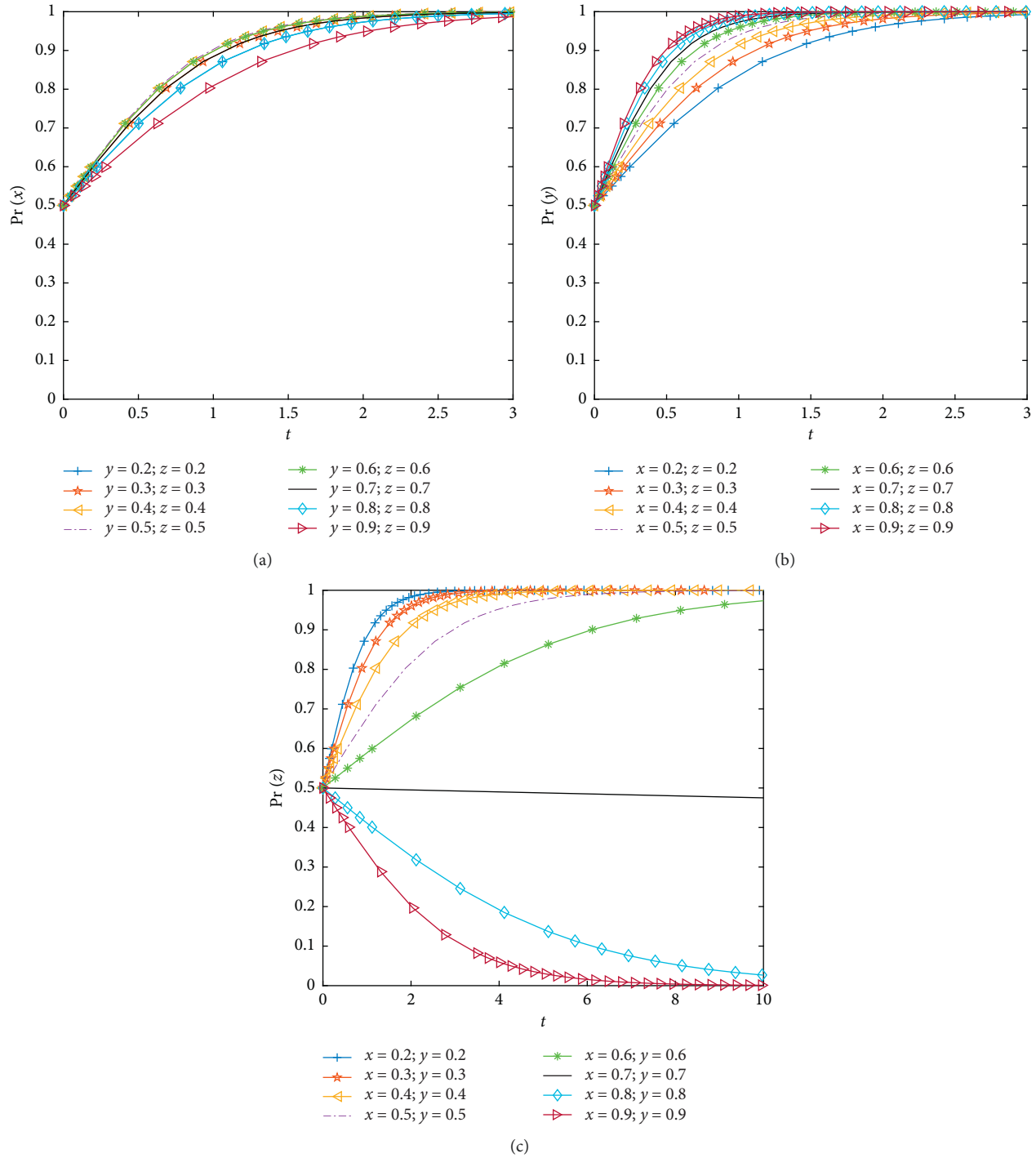


FIGURE 2: (a) Evolution curve of x when y and z change. (b) Evolution curve of y when x and z change. (c) Evolution curve of z when x and y change.

the optimal strategy, and the smaller the initial proportion, the longer the time to reach the optimal strategy.

Now, taking $x = 0.3$, $y = 0.5$, and $z = 0.7$ as an example, the evolutionary trend of the organization, miners, and managers is demonstrated as shown in Figure 5. The final evolution of the three agents is {positive incentive, safe operation, safety supervision}, which confirms the stability of the equilibrium point $E_8(1, 1, 1)$. Therefore, the equilibrium point $E_8(1, 1, 1)$ is the only ideal steady state.

3.2. Stability of the Dynamical Game System with Incentive-Punishment Strategy. In order to make the dynamic game system reach the evolutionary steady state more quickly, under the stable condition that satisfies the ideal state point $E_8(1, 1, 1)$, first, we increase the incentives (performance pay and bonuses) for the safe operation of miners and the safety supervision of managers; the penalty costs for unsafe operations of miners and no supervision and even power rent seeking by managers remain unchanged, that is, the

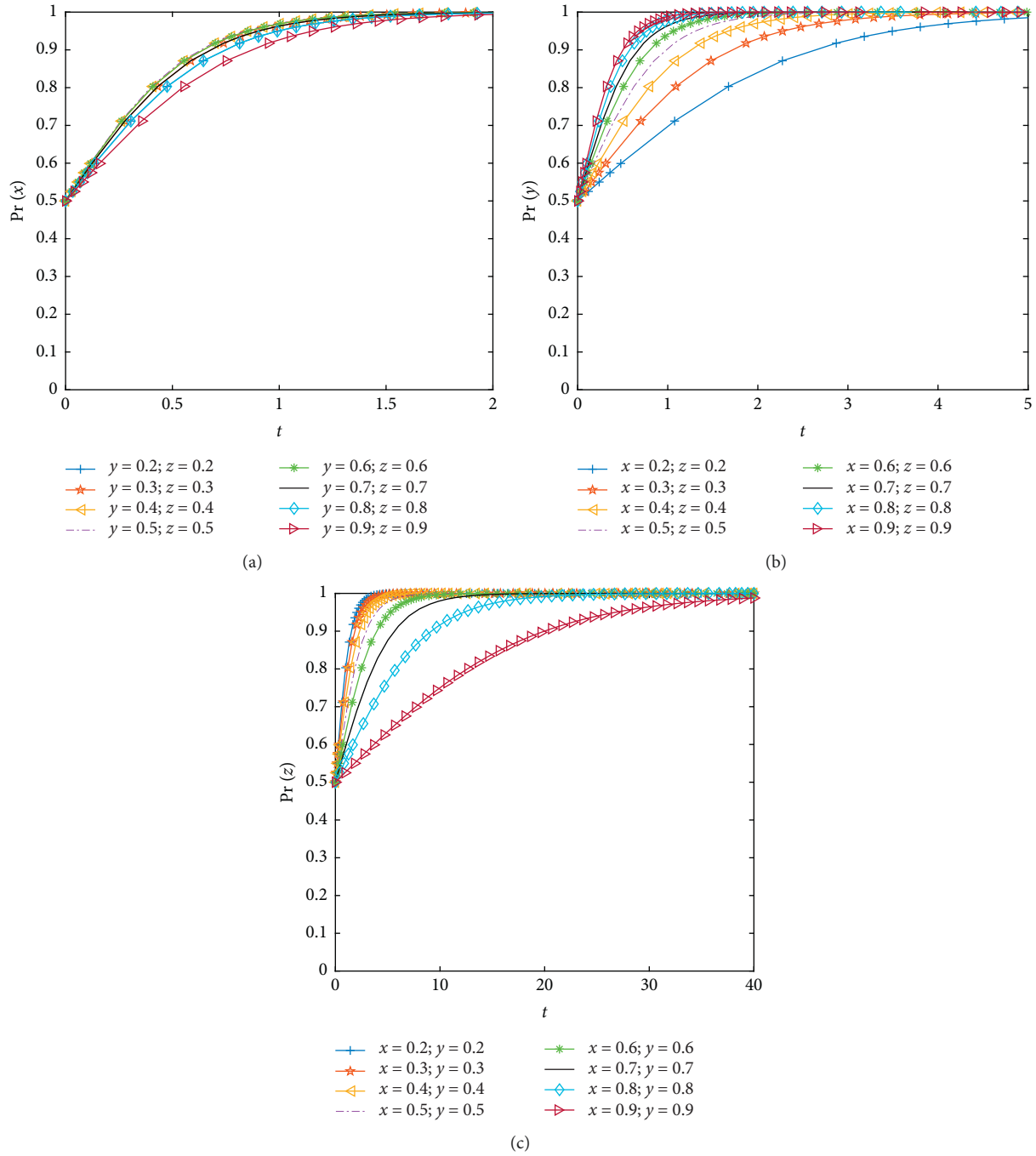


FIGURE 3: (a) Evolution curve of x when y and z change. (b) Evolution curve of y when x and z change. (c) Evolution curve of z when x and y change.

parameters are adjusted to $c_1 = 22$, $r_1 = 24$, $c_2 = 21$, $r_2 = 22$, $s_3 = 7$, $t_1 = 4$, $t_2 = 2$, $s_1 = 4$, and $s_5 = 7$, and other parameters are unchanged; the evolution result of the dynamic game system is shown in Figure 6. In addition, we increase the penalty costs for unsafe operations of miners and no supervision and even power rent seeking of managers, and the incentives (performance pay and bonuses) for the safe operation of miners and the strict supervision of managers remain unchanged, that is, the parameters are adjusted to $c_5 = 9$ and $s_4 = 0$, and other parameters are unchanged; the

evolution result of the dynamic game system is shown in Figure 7. Finally, we also increase the incentives (performance pay and bonuses) for the safe operation of miners and the safety supervision of managers and the penalty costs for unsafe operation of miners and no supervision and even power rent seeking of managers, that is, the parameters are adjusted to $c_1 = 22$, $r_1 = 24$, $c_2 = 21$, $r_2 = 22$, $s_3 = 7$, $t_1 = 4$, $t_2 = 2$, $s_1 = 4$, $s_5 = 7$, $c_5 = 9$, and $s_4 = 0$, and other parameters are unchanged; the evolution result of the dynamic game system is shown in Figure 8.

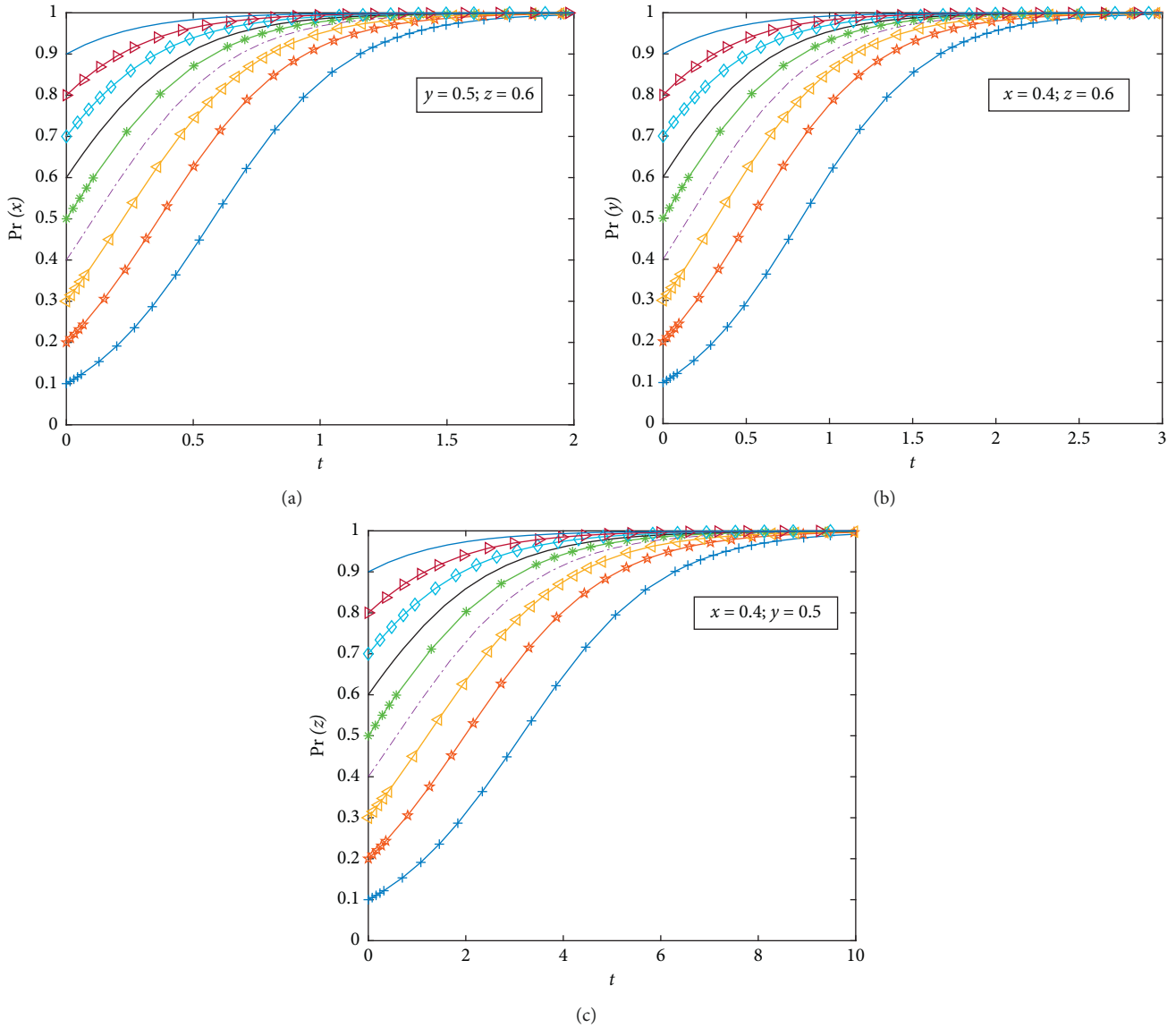


FIGURE 4: (a) The evolution curve of x when $y = 0.5$ and $z = 0.6$. (b) The evolution curve of y when $x = 0.4$ and $z = 0.6$. (c) The evolution curve of z when $x = 0.4$ and $y = 0.5$.

By comparing Figures 5–8, it can be found that the dynamic game system needs 5 s to reach a steady state in the initial setting; when only the reward strategy is adopted, the system can be stabilized in 2.5 s, which can be reduced by half; when only the penalty strategy is adopted, the system can be stabilized in 3.5 s; when the reward strategy and the penalty strategy are adopted at the same time, the system can be stabilized in 2 s. The above numerical simulation results show that the combination of positive incentive policies and strict penalties policies can make the game model reach a stable state more quickly.

4. Discussion

Through the decision-making dynamic replication analysis, evolution stability analysis and numerical simulation experiments among the three stakeholders of the organization,

miners, and managers in coal-mine safety production, the results of this paper include the following three parts:

- (1) From the dynamic replication equation of the decision making, the proportion of decision making of organization's "positive incentives" is related to the proportion of miners' "safety operation" and the proportion of decision making under managers' safety supervision; the proportion of miners' "safety operation" is related to the proportion of decision making of organization's "positive incentives" and managers' safety supervision; the proportion of decision making under managers' safety supervision is related to the proportion of organization's "positive incentives" and miners' "safety operation." Specifically, whether the organization decides to adopt the positive incentives will be directly affected by whether the miner adopts the safe operation and whether the manager adopts

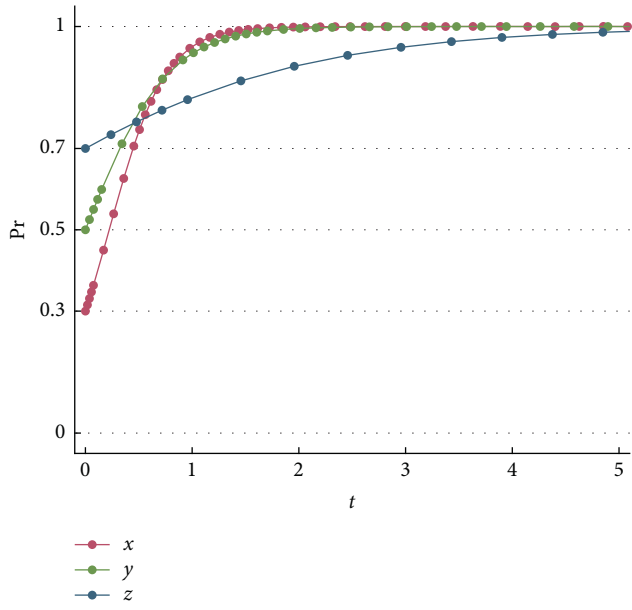


FIGURE 5: The final evolution result of $E_8(1, 1, 1)$ with the initial setting.

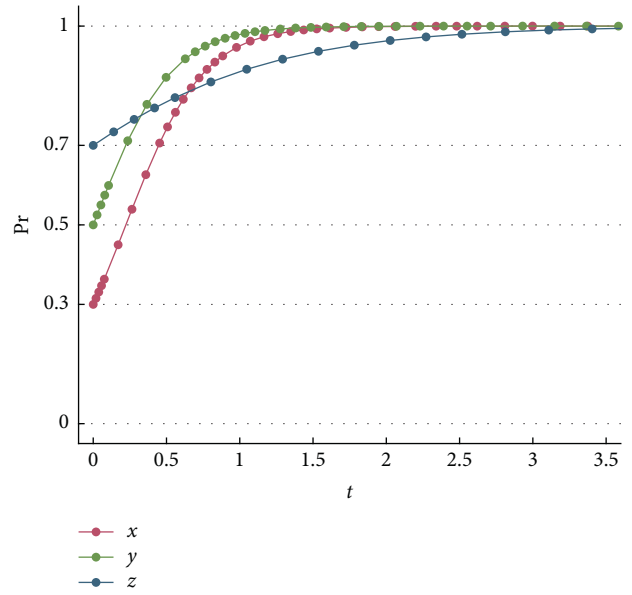


FIGURE 7: The final evolution result of $E_8(1, 1, 1)$ with punishment strategy.

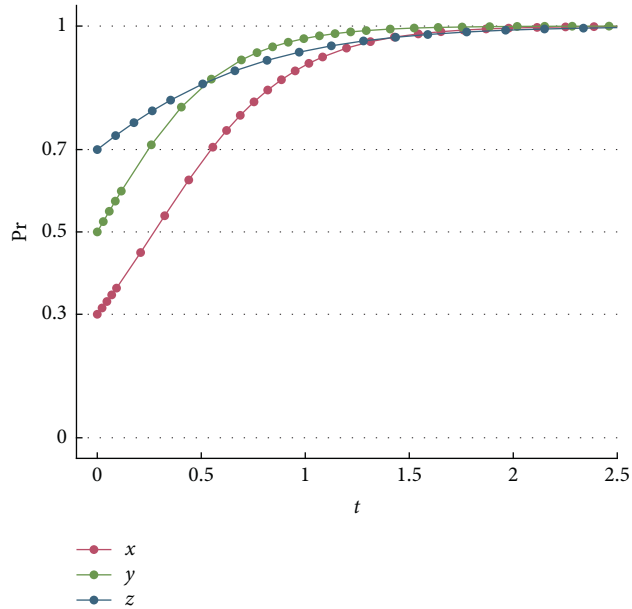


FIGURE 6: The final evolution result of $E_8(1, 1, 1)$ with incentive strategy.

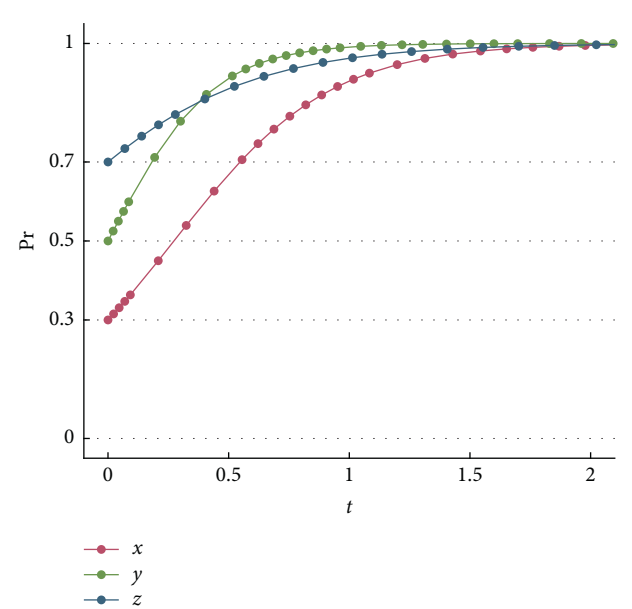


FIGURE 8: The final evolution result of $E_8(1, 1, 1)$ with incentive-punishment strategy.

safety supervision; whether the miner decides to adopt the safe operation decision will be directly affected by whether the organization adopts the positive incentives and whether the manager adopts safety supervision. Whether the manager adopts the decision of safety supervision is influenced by whether the organization adopts the positive incentives and whether miners adopt safe operation. The above result shows that the decision making of organization, miners, and managers interact with each other, the bridge among the three agents is the managers, so the existing static

analyses of the game between two stakeholders has certain limitations. [31]. In the process of coal-mine safety production, it is necessary to make clear the influence relationship among the three.

- (2) From the analysis on evolution stability, we can see that these equilibrium points of $E_1(0, 0, 0)$, $E_2(0, 0, 1)$, $E_5(1, 0, 0)$, and $E_6(1, 0, 1)$ are not stable state, indicating that if the miners choose unsafe operation, no matter what strategy the organization and managers adopt, the evolutionary game model will not reach the stable state. From the perspective of

evolutionary game, it is proved that the unsafe behavior of miners is the most direct and main cause of coal-mine safety accidents [2–4] and the decision making of miners plays an important role in the operation of coal-mine safety production [29–31, 50, 51]. In addition, the equilibrium point $E_3(0, 1, 0)$ is not stable state. Even if the miners take safe operation at the initial stage, they will gradually evolve the unsafe operation to alleviate the high work stress if the organization has been in general incentive state and the manager has not implemented strict supervision. And in the end, the miners tend to gain psychological benefits from unsafe operation and adopt unsafe operation. Furthermore, the equilibrium points that can make the evolutionary game model reach a steady state are $E_4(0, 1, 1)$, $E_7(1, 1, 0)$, and $E_8(1, 1, 1)$. This means that certain positive incentive from organization and certain safety supervision from managers are necessary for the miners to adopt safety operation; otherwise, the miners lack the driving force to conduct safety operation. The organization and managers should realize that the incentive type mode and strict supervision for safety production are effective driving factors for miners to take safe operation.

- (3) From the numerical simulation results, we can see that only the equilibrium point $E_8(1, 1, 1)$ is the ideal steady state, and when three conditions are satisfied, the three agents can achieve the ideal state: ① the net profits of organization's positive incentive are greater than the net profits of the general incentive; ② the net profits of the unsafe operation are less than the net profits of safe operation; and ③ the safety supervision cost of managers is less than the profits. The three stakeholders who are the organization, miners, and managers can achieve the ideal condition, that is, the ideal safety production state of organization adopting positive incentive, miners adopting safe operation, and managers taking safety supervision. It can be seen that the final evolutionary state of the game model of the organization, miners, and managers will depend on the organization's incentive costs, organizational benefits, the net profits of miners, incentives and costs for managers taking safety supervision, etc [52]. In addition, we also find that the higher the initial proportion of the strategy portfolio of miners and managers, the longer the time of organization converging to a stable ideal state, which shows that when the initial proportion of the miners choosing safe operation and the managers adopting safety supervision is high, the organization will slow down the rate of positive incentives. The higher the initial proportion of the strategy portfolio of organization and managers, the shorter the time of miners converging to a stable ideal state, which shows that the cooperation between the organization and managers can speed up

the decision-making of the miners' safe operation. The higher the initial proportion of the strategy portfolio of organization and miners, the longer the time of managers converging to a stable ideal state, which shows that when the initial proportion of miners adopting safe operation and organization adopting positive incentives is high, the managers will relax the safety supervision for the miners. The results of this numerical simulation reflect an unreasonable game between the players inside the coal-mine safety production system, which is a problem that we need to pay attention to and improve. Furthermore, the strategy portfolio with a relatively high initial proportion of three agents converges more quickly to an ideal state than a relatively low strategy portfolio. Finally, we find that the combination of positive incentive policies and strict penalties policies can make the game model reach a stable state more quickly [28]. In summary, this study shows that the efficient cooperation among the organization (positive incentives), miners (safe operation), and managers (safety supervision) can make the coal-mine safety production system quickly enter the ideal state of stable and safe operation.

5. Conclusions

Through the evolution analysis on the decision-making behavior of three stakeholders, namely, the organization, miners, and managers, it is concluded that the incentive cost and net profits of organization, supervision costs and profits of managers, and net profits of miners are crucial factors to achieve the ideal decision making of stakeholders, and the combination of positive incentive policies and strict punishment policies are the key to ensuring that the game model quickly reaches a stable state; the conclusions are as follows:

- (1) As the senior manager of coal mining enterprise, the organization can appropriately improve the level of safety incentives and formulate reward and punishment mechanisms and provide reasonable economic and policy support for safety production so that enterprises can realize the transition from the penalty type management mode for safety production to the incentive-punishment management mode for safety production. For the organization supervision, scientific methods shall be adopted to promote the efficiency of safety production. When both the miners and managers adopt safe strategy, organizations should make more rewards rather than reduce rewards. At the same time, it shall be realized that the deterrent effect will decline in case of blindly intensifying supervision and penalty, and the game among the organization, miners, and managers will be more serious. The organization can adopt market-oriented means, with the stimulation of economic interests, publicity, guidance, and policy support so as to enable the coal mining enterprises to internalize

the goal of improving the safety production. The organization and managers can use effective safety education to raise miners' awareness and enthusiasm for safety production and create a good climate for safety production. The expression mechanism of the miners' interests should be provided to ensure the expression of miners' interests and psychological appeals and enable miners to positively and effectively communicate with managers, such as strengthening the construction of trade unions and providing specialized mental health and safety counseling offices to communicate and guide on the psychological pressures of miners.

- (2) As the most direct supervisor of first-line miners, the managers should strengthen the safety supervision of miners' production operations; regardless of whether miners choose safe operation or unsafe operation, they should strengthen supervision of miners, and they should promote the safety climate of the group through cultural driving and then promote the miners' deep sense of safety awareness and compliance practices. Managers should strengthen the safety culture in the group and create safety responsibility beliefs of team, safety responsibility mentality, and safety responsibility behaviors of team. Furthermore, managers can provide counseling and education for the "responsibility" of miners, such as holding speeches and photography competitions related to safety responsibility. In this way, the awareness of the safety behavior of miners is increased, and the possibility of violations is reduced.
- (3) Miners are the direct executor of coal-mine production and play a key role in avoiding safety accidents. In order to positively respond to the safety attention of organizations and managers and to better protect their own safety and the expression of their own interests, the miners should not only strengthen their own safety awareness and safety attitude and choose safe operation in their work but also form a positive and habitual awareness of rights protection. When individuals face greater work stress or psychological pressure, they should positively communicate with managers and organizational departments in order to get help from them and thus relieve stress and work safe, instead of venting emotions through unsafe operation. When personal interests are infringed, they should positively report to the trade unions and properly and effectively protect their rights through legal channels, rather than blindly solving problems.

In the study, the decision-making behavior evolution path and evolution law of three stakeholders of organization, miners, and managers are revealed, and the stable conditions for the main decision to reach the ideal state are found out. The simulation is carried out to provide theoretical reference and practical guidance for the organization safety incentive

mode, miner safety operation strategy, and manager safety supervision decision making. Next, the research will focus on the tetragonal evolutionary game of organization, group, miners, and managers; combined with the classic paradigm of cognitive neuroscience, using event-related potential technology, the research will focus on further experiment verification of the evolution of the decision-making behavior of the organization, group, miners, and managers to make the verification process and result more objective, scientific, and referential.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Authors' Contributions

Yan Li and Yan Zhang are the co-first authors. They contributed equally to this paper.

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