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Research Article

Simulation Research on the Effectiveness of a Multiagent Mine Safety Supervision System and Its Verification

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A Computable Mine Safety Supervision (CMSS) model is constructed based on agent-based modeling and simulation (ABMS) technology and the conservation of resources (COR). This model aims to solve the mining safety problems involved with illegal mining operations and burnout among mining supervisors, in China. The model includes several types of agents: supervision agents, decision support agents, functional coordination agents, and miner agents, and it uses the Netlogo simulation platform to simulate the influence of reward and punishment on agent behavior. The simulation determines the decision support degree to gauge the influence of functional coordination and miner behavior on the burnout rate of supervision agents. We analyze the macroscopic emergence law of the simulation results. The results show the following: (1) Job Situation Adaptability (JSA) $\in [-6.02, 2.64] \cup [16.9, 21.93]$, which uses a reward strategy to guide miners to choose safe behavior and (2) JSA $\in [2.64, 16.9]$, which uses a punishment strategy to restrict unsafe behavior. The decision support coefficient S_c has the greatest influence on the supervision agent's job burnout. The functional coordination coefficient F_c has the second highest influence on job burnout and the processing effectiveness coefficient E_c has the least influence. According to the simulation results, suggestions for improving the mine safety supervision system are put forward and an improved safety management decision-making basis for reducing mine accidents is provided.

1. Introduction

Mine accidents restrict the development of many mining enterprises. Most accidents are the result of miners practicing illegal operations. Mining enterprises typically implement a safety supervision system in response to accidents; however, the frequency of mining accidents suggests that many miners are indifferent to, or choose not to comply with, these systems [1–3]. Many supervisors experience job burnout because of the long-term pressures of their work; such pressures include finding ways to address the unsafe behavior of the miners. The frequent occurrence of unsafe miner behavior reflects the persistent problem of safety management in mines. If this problem is not solved, mine accidents will continue to occur. This article proposes an optimized mine safety supervision system.

From the existing research, we find that the effectiveness of mine safety supervision systems is best analyzed by (1) qualitative analysis, based on case interviews; (2) specific research, based on empirical methods; and (3) tendency analysis, based on expert theoretical judgments about the relevant technology (Social Cognitive Occupational Theory, EAP, Maslow's Hierarchy of Needs Theory) [4–8]. Cheng and Zhong and others have studied the management characteristics of miners from the perspective of social science. They considered various related factors, including safety supervision [9], safety management systems [10], and organizational factors and managerial behavior [11]. Maslach and Jackson used a three-dimensional model to define job burnout. They considered that job burnout is a psychological syndrome, which includes three aspects: emotional exhaustion, personality disintegration, and sense of the loss of personal accomplishment [12, 13]. In 2003, Li used a questionnaire to dynamically define and measure job burnout [14]. In 2013, Hong and Hui and others proposed a study method based on dynamic simulation. This paper investigates the phenomenon of job burnout of supervisory agents in coal mine enterprises [15, 16]. Current research methods may be categorized into two types. The first is the simulation of system dynamics (SD) and the second is a static research method based on case interviews, empirical analysis, and structural equation models. ABMS technology is widely used in coal industry, Zhao et al. put forward a coal mine safety evaluation model based on ABMS evidence theory and verified the validity of the model [17]. Qi et al. constructed the agent model of a coal mine safety supervision system with multiagent modeling and investigated a simulation system based on Netlogo. The decision mechanism of coal mine safety supervision performance is analyzed by observing dynamic changes of the supervision activities, system risks, and success rate of processing violations [18]. Chen et al. based on agent Modeling and simulation technology, combined with the complex adaptation theory, built the behavior decision-making system model of coal mine workers, using the netlogo simulation platform, and analyzed the impact of unsafe behavior punishment system on behavior selection [19]. Cai et al. based on multiagent technology, a virtual coal mine platform for risk behavior simulation, presented to model and simulate the human-machine environment related risk factors in underground coalmines. Experimental results show that the proposed models can create more realistic and reasonable behaviors in virtual coal mine environments, which can improve miners' risk awareness and further train miners' emergent decision-making ability when facing unexpected underground situations [20]. However, few scholars have studied the job burnout phenomenon that afflicts mine supervisors. Qualitative analysis ignores the mutual relationship between supervisors and the operational process, and it does not consider how the job burnout phenomenon affects supervisors and their ability to do their jobs properly.

The optimization problem of a mine safety supervision system does not comprehensively consider miners' illegal operations or supervisors' level of stress and burnout. SD-based research ignores the interaction between agents while emphasizing microscopic conditions, while static studies do not consider time factors. ABMS provides a new method for optimizing research about mine safety supervision systems [21–23]. ABMS emphasizes the microscopic behavior of system-related agents, and it also considers time factors. Therefore, based on ABMS, this paper abstracts the key elements of the mine safety supervision system, characterizes the interaction among various elements, and builds a Computable Mine Safety Supervision (CMSS) model. It then uses the Netlogo simulation platform to implement and verify the model. This study aims to explore the macroscopic emergence law caused by agents' microscopic behavior. The analysis of the simulation results helps to improve the applicability of safety management decisions and reduce the incidence of mine accidents.

2. Computable Miner Safety Supervision Model Construction

2.1. Job Situation Adaptability (JSA) and Conservation of Resources. JSA refers to the emotional experience of miners while they are at work and when they are conducting work related activities [24–27]. It includes the general views of miners about issues related to safety management systems, salary, and work environment. Typically, the higher the JSA, the better the employee satisfaction and the more inclined the employee to choose safe behaviors. The lower the JSA, the lower the employee satisfaction and the more inclined the employee to choose unsafe behaviors. The Conservation of Resources Theory [9, 28, 29] provides a theoretical basis for tracking the phenomenon of agent burnout. It holds that individuals tend to preserve the resources they think are most precious. If precious resources are lost, the individuals themselves will feel threatened. If such resources can somehow be supplemented over time, the exhaustion of such resources can be reduced. In the open-pit mine agent safety supervision system based on COR theory, miners lose resources because of their work needs. When miners do not have enough psychological resources to maintain a sense of psychological balance, personal emotions will be affected, which will affect the miners' work efficiency and cause economic losses for the mining enterprises. In the mine safety management system, the decision-making body and the functional limbs will affect the individual resources of the miners. The commitment and help of the organization will enhance the satisfaction of the miners and supplement the miners' own resources. On the contrary, if the organization does not provide enough support, the miners will feel lost, which will lead to the reduction of their personal resources. Individuals rely on the mining organization because it is the group to which they belong. Organizational decision-making and actions will complement the organization's own resources.

(1) The information exchange process between miner agents is divided into four categories: independent, information transfer, information feedback, and interaction (Figure 1).

(2) The job situation adaptability (JSA) index is used as the basis for analyzing the behavior selection of miner agents. Considering the spread of unsafe behavior among miners, it simulates the macroscopic emergence phenomenon caused by the microbehavior of miners under different reward and punishment strategies.

(3) Based on the Conservation of Resources (COR) theory, this paper constructs a supervision agent psychological resource index system, simulates job burnout caused by different agents' microbehaviorial choices, and examines three specific factors: emotional exhaustion, personality disintegration, and personal achievement.

(4) Each agent involved in the mine safety supervision system experiences mobility and can move freely to any position in the simulated work world.

(5) Each agent has bounded rationality, communicates and evolves in the process of interaction with other agents in the established situation, learns from other agents, and is restricted by the simulation's interaction rules.

The CMSS model architecture is shown in Figure 2. The mine environment agent model, the miner agent model, the supervision agent model, the functional agent model, and

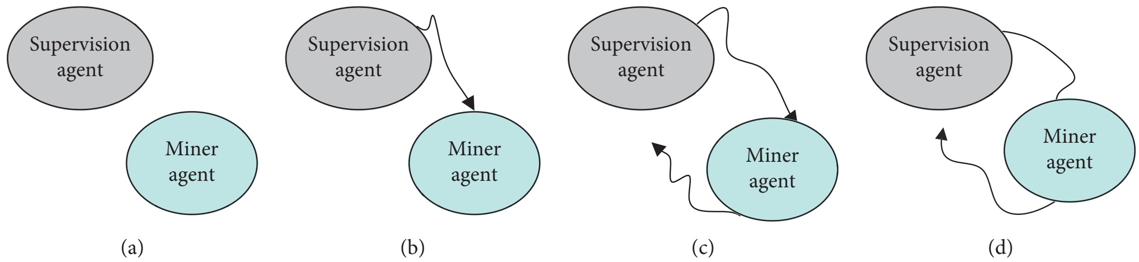

Figure 1: Unsafe behavior propagation model. (a) Mutual independence. (b) Information transfer. (c) Information feedback. (d) Information interaction.

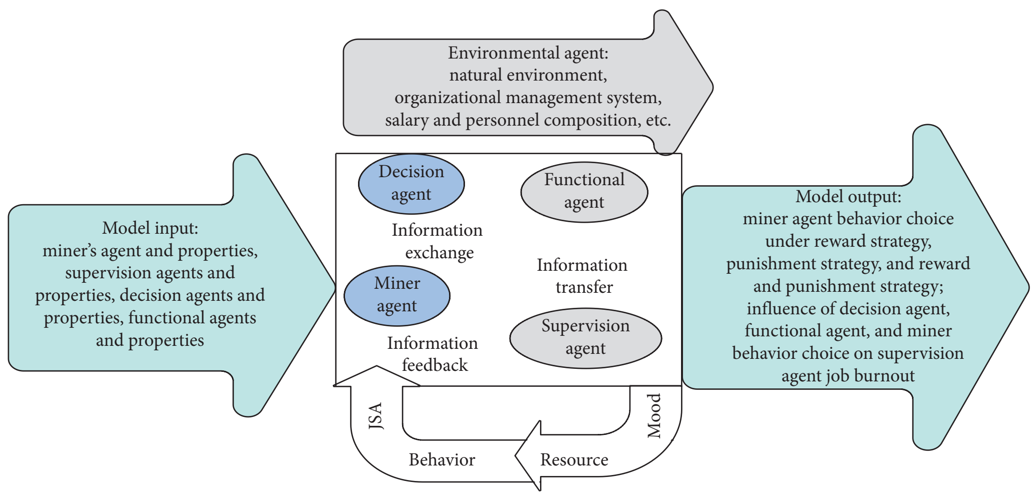

Figure 2: CMSS conceptual model.

the decision-making agent model are inputs, and the key variables and elements in the mine safety supervision process are depicted. The interaction among agents under the established rules is simulated. The activities that interact with each other are dynamic inputs and outputs. Finally, the quantitative effect of the number of miner agents is used to reflect the utility of the reward and punishment strategy.

The CMSS model inputs include the environment agent model, the miner agent model, the supervision agent model, the decision agent model, and the functional agent model. Each type of agent model abstracts key attributes to construct the simulation model.

2.1.1. Environment Agent Properties

(1) The environmental location, that is, the size of the Netlogo simulation world is 100×100, according to the density of the miner population. It totals 10,000 tiles, represented by coordinates in the simulation world, and the value is (X, Y), where $X, Y \in (-50, 50)$.

(2) Enterprise losses caused by unsafe behavior are represented by L. The model considers economic losses, affected by factors such as safety management inputs and machinery and equipment inputs; the value range is set to $[0, 50]$.

2.1.2. Miner Agent Properties

(1) The scope of the impact of the miner agent on the environment, which is represented by P_1, has a value of 0 to 5 in the simulated world.

(2) The scope of the supervision of illegal operations—that is, the range in which miners are found to be conducting illegal actions—is represented by a grid in the Netlogo network world and has a value of P_2.

(3) The probability of the selection of unsafe behavior, N_1, has a value range set to $N_1 \in (0, 1)$.

(4) The safety behavior cost is C_1. Factors that influence safety behavior include working time, working environment, and work intensity. In this paper, the safety behavior cost C_1 is expressed as work fatigue K, and K is equivalent to the growth rate of working pressure. The specific formula is as follows:

$$K = 8 \sum_{j=1}^{n} \left(1 + i_j\right) + \partial. \tag{1}$$

In formula (1), n represents the time of continuous operation, i_j represents the growth rate of the working pressure, the value of $i_j \in [2\%, 5\%]$, and ε is the remainder, representing the bearing capacity of different miners on the working pressure. The random value falls between 0–8.

(5) The unsafe behavioral benefit R_2 is measured by the physical and mental valence W_1 and also by the time valence W_2 of unsafe behavior under the reward and punishment strategy. The physical and mental valence refers to the psychological and physiological satisfaction of miners who commit unsafe behavior, and the value range is set to [0, 30]. Time valence refers to the time saved by miners using unsafe behavior, and the value is set to [0, 30].

(6) Duration of illegal operation: the probability of illegal operations being discovered depends greatly on the duration of the illegal operation. We assume that the duration value is T_c; then, the longer the T_c, the more likely the illegal operation will be discovered.

(7) Processing effectiveness coefficient: after the supervision agent successfully processes a violation operation, the miners who are processed as having committed this action may still select the illegal operation in the next production operation. Therefore, the processing effectiveness coefficient is defined and the value is assumed to be E_c.

2.1.3. Supervision Agent Properties

(1) The visual range is determined as the scope of supervision that the supervision agent in the surrounding environment has over the violation behavior; this is represented by a grid in the Netlogo network world, and it is represented by P_3.

(2) The probability of intervening in unsafe behavior, N_2, has a value range set to $N_2 \in (0, 1)$.

(3) The penalties for unsafe acts, i.e., the cost of unsafe acts, are denoted as C_2. The survey shows that there are many ways to punish unsafe behaviors, including training, fines, on-the-job action, and demotion. The value range of fine m is set to [0, 30]. Based on the principle of behavioral decision cost estimation, the training, waiting, and demotion costs are $0.3M$, $0.8M$, and $1.3M$, respectively. Then, $C_2 = 0.3M + M + 0.8M + 1.3M = 3.4M$.

(4) The reward level for safe behavior—that is, the "return" given for safe behavior R_1—includes a bonus and other measures of appreciation. The value range of bonus O is set to [0, 30] based on the principle of behavioral decision cost estimation. The appreciation gain is $1.3O$, and then $R_1 = O + 1.3O = 2.3O$.

(5) The inherent quantity of the agent resource is the natural attribute of the supervision agent, assuming the value is R_0.

(6) Resource processing consumption reflects the psychological resources consumed by the supervision agent to deal with a violation of the rules, assuming the value is R_c.

(7) The amount of resources supported by the supervision agent includes the amount of resource support provided to the agent when the agent handles the violation, and the assumed value is R_u.

(8) Functional coordination resources include the amount of resource support given by the functional coordination department when the agent handles violations, assuming the value is R_f.

(9) The event processing success rate reflects the success of the supervision agent in handling the illegal operation, assuming the value is P_j.

2.1.4. Decision Agent Properties. The decision agent is the superior manager of the supervision agent in the mine safety supervision system. In the CMSS model, the main function of the decision agent is to support the supervision agent according to the details of the event and the strength of the support agent is processed by the supervision agent's event success rate (P_j). When P_j is higher than the expected value of the decision agent, more support will be provided. If P_j is lower than the expected value of the decision agent, the support obtained will be relatively small. The properties are as follows:

(1) Number of agents: the role of the decision agent in the security management system is reflected in the support of the supervision agent. In order to simplify the simulation system, only one decision agent is set.

(2) Decision support coefficient: the decision agent supports the supervision agent. The assumption is S_c, $S_c \in [-1, 1]$. When S_c has the value 1, the decision agent fully supports the work of the agent and provides sufficient support resources. When the S_c value is 0, the decision agent maintains neutral support for the supervision agent. When the S_c value is -1, the decision agent rejects the work of the supervision agent and does not provide any support. S_c is affected by the event processing success rate P_j and is positively correlated.

2.1.5. Functional Agent Properties. The functional agent is the relevant functional department in the mine safety supervision system. In the CMSS model, the functional agent cooperates with the supervision agent according to the different nature of the event, and the functional agent is also affected by P_j. When P_j is higher than the expected value of the functional agent, the agent will obtain greater support strength. If P_j is lower than the expected value of the functional agent, the obtained support strength will be relatively small. The functional agent attributes include the following:

(1) Number of agents: the role of the functional agent in the safety management system is reflected in the corresponding cooperation with the supervision agent, including efforts such as medical services and rescue measures. To simplify the simulation system, a functional agent is set up.

(2) The functional coordination coefficient is the functional coordination degree provided by the functional agent to the supervision agent when dealing with violations, assuming F_c, $F_c \in [-1, 1]$. When the value of F_c is 1, the functional agent fully cooperates with the supervision of the agent. When the value of F_c is 0, the degree of coordination of the functional agent to the supervision agent remains neutral. When the value of F_c is −1, the functional agent is opposed by the work performance of the supervision agent and does not provide any matching resources. F_c is affected by the event processing success rate P_j and is positively correlated.

2.2. Behavioral Simulation

2.2.1. Behavior Selection of the Miner Agent under the Effect of Simulated Reward and Punishment Strategies. Behavioral economics believes that the choice of individual behavior is the result of utility or the maximization of benefits. Under reward and punishment strategies, miner agents have different degrees of difference in terms of psychological activities, values, and ways of thinking and decision-making. The loss of economic benefits affects the work situation adaptability of the miner agent to varying degrees. When the work situation adaptability is reduced to a certain threshold, the miner agent will choose unsafe behavior, and the selection of unsafe behavior greatly increases the incidence of mine accidents.

Based on the multiagent simulation theory, the CMSS model simulates the behavior selection of miner agents under the three dimensions of reward strategy, punishment strategy, and reward and punishment strategy, and it improves the mine safety supervision system through the analysis of macroscopic emergence rules.

2.2.2. Impact of Decision Agent Status on Supervision Job Burnout. The decision agent status is determined by the decision support coefficient (S_c) and plays a role in the simulation by influencing the decision resources. The decision agent in the CMSS model acts on the supervision agent in aspects including behavior affirmation, behavior neutrality, and behavior negation. The status of the decision is affected by the impact of P_j.

(1) Behavior Is Affirmation. When $S_c \in (0, 1)$, the decision agent has a positive attitude toward the supervision work of the agent and provides corresponding support resources. The larger the S_c, the higher the amount of resource support obtained by the supervision agent.

(2) Behavioral Neutrality. When $S_c = 0$, the decision-making agent has a neutral attitude toward the supervision work of the agent, neither giving nor withdrawing resource support.

(3) Behavioral Negation. When $S_c \in [-1, 0)$, the decision agent has a negative attitude toward the supervision work of the agent, leading to resource punishment; the lower the S_c, the greater the punishment.

2.2.3. Effect of Simulated Agent Status on Job Burnout of the Supervision Agent. The functional agent status is determined by the functional coordination coefficient F_c and exerts its effectiveness by influencing the functional resources. The actions taken by the functional agent in the CMSS model to monitor the agent include functional coordination, functional neutrality, and functional impediment. The functional coordination state is subject to P_j.

(1) Functional Coordination. When $F_c \in (0, 1)$, the functional agent cooperates with the supervision agent and provides corresponding functional resources. The larger the F_c, the greater the functional resources obtained by the supervision agent from the functional agent.

(2) Functional Neutrality. When $F_c = 0$, the functional agent has a neutral attitude toward the work of the supervision agent and neither provides functional support nor inflicts resource punishment.

(3) Functional Impediments. When $F_c \in [-1, 0)$, the functional agent refuses to monitor the work of the agent, and thus resource punishment is imposed. The lower the F_c, the greater the punishment.

2.2.4. Effect of Simulated Miner Behavior Choice on Supervision Job Burnout. The influence of miners' behavior choices on the burnout rate of supervisors is determined by the processing effectiveness coefficient (E_c). Any change in $E_c \in (0, 1)$ or E_c in the CMSS model affects the event processing success rate. P_j, simulating the job burnout of the supervision agent under the action of different values of E_c, is conducive to improving the effectiveness of mine supervision.

2.3. Model Output. Unsafe behavior selection by a miner agent in the CMSS model creates three kinds of quantitative macroemergence phenomena that may be researched, namely, the quantitative output of the number of safe and unsafe behavior choices made by miners may be researched from the three aspects of reward strategy, punishment strategy, and reward and punishment strategy.

The Maslach Burnout Inventory (MBI) contains three subscales: emotional exhaustion, personality disintegration, and personal achievement [29, 30]. Emotional exhaustion refers to the sense of exhaustion caused by the excessive consumption of the emotional resources of the supervising agent. Disintegration of personality refers to the alienated state of the miner agent. Personal achievement refers to the reduction of the sense of personal accomplishment caused by frustration encountered during the supervision of the miner agent's work.

The CMSS model simulates these three dimensions: decision agent status, functional agent status, and miner behavior selection, and the model then studies the influence of these factors on-the-job burnout rate of the supervision agent [31, 32]. The macro output of the CMSS model monitors the number of changes that occur in the factors of the emotional exhaustion, personality disintegration, and personal achievement of the agent under the action of the different attributes of each dimension.

3. Implementation and Verification of the CMSS Model

3.1. Implementation of the CMSS Model. The program structure of the multiagent simulation platform based on the CMSS model is shown in Figure 3. The visual modeling editor is used to construct various submodels of the mine safety supervision system, including the environmental agent submodel, the supervision agent submodel, the decision agent submodel, the functional agent submodel, and the miner agent submodel, according to the set agent interaction rules. The model data is initialized, and then the simulation platform Netlogo reads the model data and simulates the microbehavior between agent and environment and between agent and agent according to the CMSS model, and it then visualizes the output result through the regular change of the simulation data. After the simulation experiment, the result interpreter is diagrammed and used to statistically analyze the macroscopic laws that emerge from the microscopic behavior.

3.2. Interaction Rules of the CMSS Model

3.2.1. Unsafe Behavior Selection Rules. The CMSS model studies the miner agent behavior selection mechanism based on the job situation adaptability (JSA). To some extent, the JSA has a positive correlation with the miner's performance, so the JSA function is defined by the comprehensive performance benefit.

(1) Performance Income Calculation. Performance gains are based on the operator's performance, considering performance gains, safe behavior, and unsafe behavior. Safety performance returns at time t are defined as G_1, and the unsafe performance return is defined as G_2. The specific calculation is as follows.

Safety performance income at $1t$:

$$G_{1t} = N_{2t} \times (R_{1t} - C_{1t}) + (1 - N_{2t}) \times (R_{1t} - C_{1t}). \quad (2)$$

Unsafe behavioral performance gains at $2t$:

$$G_{2t} = N_{2t} \times (R_{2t} - C_{2t} - L_t) + (1 - N_{2t}) \times (R_{2t} - L_t). \quad (3)$$

(2) T-Time JSA Function

$$\mathrm{JSA}_t = (1 - N_{1t}) \times G_{1t} + N_{1t} \times G_{2t}. \quad (4)$$

(3) JSA Changes Based on the Number of Simulation Steps. The mine operation is a continuous change process, and the JSA of the operator also changes continuously with time. The JSA_t is affected by JSA_{t-1} as follows:

$$\begin{aligned} \mathrm{JSA}_t &= \mathrm{JSA}_{t-1} + a, \quad \mathrm{JSA}_t < 0, \\ \mathrm{JSA}_t &= \mathrm{JSA}_{t-1} - b, \quad \mathrm{JSA}_t \geq 0. \end{aligned} \quad (5)$$

As shown in formula (5), when $\mathrm{JSA}_{t-1} < 0$, after a shift in the mood, JSA_t will rebound to a, resulting in a decrease in miners' negative emotions. When $\mathrm{JSA}_{t-1} \geq 0$, after the miners continue to work on a shift, the JSA_t will lower to b, which will reduce the positive mood of the miners; in this scenario, a is gain and b is loss. Assuming that miners are more sensitive to scenario loss than to scenario gain, then $a \in (0, 8)$ and $b \in (8, 15)$.

JSA is the emotional experience of workers under the influence of performance gains. It is stipulated in the Netlogo simulation world that when the JSA is less than 0, the accumulation of negative emotions promotes the occurrence of unsafe behavior. When JSA_t is greater than 0, positive emotions begin to accumulate and suppress unsafe behavior, as shown in the following formula:

$$\mathrm{JSA}_t < 0, \mathrm{IUB}. \quad (6)$$

3.2.2. Law of Unsafe Behavioral Transmission. Negative emotions continue to decrease with JSA, and they spread during the interaction with other miner agents, causing the JSA of these other miners to decrease [33, 34]. The latter group of miners learns to imitate the unsafe behavior of the first group of miners, and this latter group is eventually involved in mine accidents. The diffusion process is affected by many factors, including the miner agent itself. This paper analyzes the personality disintegration process of miners from the perspective of unsafe behavior adaptability, and it defines the diffusion boundary problem.

(1) UBA Function. Unsafe Behavior Adaptability (UBA) is a process in which miners' positive behavioral choices are continuously reduced, causing negative emotions to spread during miner interactions. UBA is influenced by individual factors, environmental factors, and organizational management factors. Suppose that an operator has an uneasy UBA_t. The behavioral adaptive function mathematical expression is as follows:

$$\mathrm{UBA}(t) = [U_1(t), U_2(t), U_3(t), U_4(t), U_5(t)]. \quad (7)$$

$U_1(t)$ is the unsafe behavior benefit state function at time t; $U_2(t)$ is the unsafe behavior cost state function at time t; $U_3(t)$ is the state function of t time itself; $U_4(t)$ is the state-to-worker state function at time t; and $U_5(t)$ is the state function under the influence of organizational management factors at time t. Assuming the UBA function is continuously derivable, the analysis is as follows:

$(\mathrm{d}U_1(t)/\mathrm{d}t) > 0$ when the benefit of unsafe behavior increases gradually with time, the operator is more inclined to choose unsafe behavior

$(\mathrm{d}U_1(t)/\mathrm{d}t) \leq 0$ when the benefit of unsafe behavior is gradually reduced, the operator is more inclined to choose safe behavior

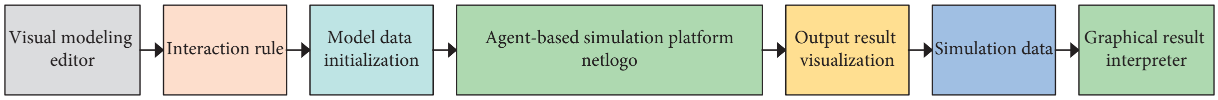

Figure 3: CMSS model program architecture.

$(\mathrm{d}U_2(t)/\mathrm{d}t) > 0$ when the cost of unsafe behavior increases with time, the increase in cost promotes the choice of safe behavior

$(\mathrm{d}U_2(t)/\mathrm{d}t) \leq 0$ in which, at the time, the reduction in the cost of unsafe behavior promotes the occurrence of unsafe behavior

Similarly, when $(\mathrm{d}U_3(t)/\mathrm{d}t) > 0$, $(\mathrm{d}U_4(t)/\mathrm{d}t) > 0$, and $(\mathrm{d}U_5(t)/\mathrm{d}t) > 0$, the operator is more inclined to unsafe behavior, and when $(\mathrm{d}U_3(t)/\mathrm{d}t) \leq 0$, $(\mathrm{d}U_4(t)/\mathrm{d}t) \leq 0$, and $(\mathrm{d}U_5(t)/\mathrm{d}t) \leq 0$, the operator chooses unsafe behavior, and the probability is small

(2) Unsafe Behavior Diffusion Boundary Problem. Not all unsafe behaviors will spread between workers, and there are diffusion boundaries for unsafe behavior. This paper analyzes the diffusion boundary of unsafe behavior from the perspective of the JSA. When $\mathrm{JSA}_t > \mathrm{JSA}_{t-1}$, the probability of the operator selecting unsafe behavior will decrease; when $\mathrm{JSA}_t < \mathrm{JSA}_{t-1}$, the operator thinks that taking safe action will not yield any return, but will instead result in the loss of self. This will render the worker more inclined to engage in unsafe behaviors, and this constitutes the basis for the spread of unsafe behavior:

$$\frac{\mathrm{d}U_1(t)}{\mathrm{d}t} > \frac{\mathrm{d}U_2(t)}{\mathrm{d}t}. \tag{8}$$

As shown in formula (8), when the growth rate of income resulting from unsafe behavior is greater than the growth rate of costs associated with unsafe behavior, unsafe behaviors will be learned and imitated among the workers, and the JSA will gradually decline, thus creating workplace insecurity and the diffusion of unsafe behavioral conditions. U_1 is represented by the unsafe behavioral benefit R_2, and U_2 is represented by the unsafe behavior cost C_2.

(3) Law of Diffusion of Unsafe Behavior. When JSA < 0 and $(\mathrm{d}U_1(t)/\mathrm{d}t) > (\mathrm{d}U_2(t)/\mathrm{d}t)$, unsafe behavior spreads among miners. Mine accidents are classified into four categories according to the degree of casualties: minor accidents, serious injuries, major fatal accidents, and major deaths:

(1) When $(\mathrm{d}U_1(t)/\mathrm{d}t) > 0$ and $(\mathrm{d}U_2(t)/\mathrm{d}t) \leq 0$, the growth rate of unsafe behavior income increases and the cost growth rate decreases continuously; in such conditions, major fatal accidents are likely to occur. In the Netlogo network world, we set the diffusion range to 4 squares: $(\mathrm{d}U_1(t)/\mathrm{d}t) > (\mathrm{d}U_2(t)/\mathrm{d}t)$.

(2) When $(\mathrm{d}U_1(t)/\mathrm{d}t) > 0$ and $(\mathrm{d}U_2(t)/\mathrm{d}t) \approx 0$, the unsatisfactory behavioral income growth rate increases, but the cost growth rate remains almost unchanged, which contributes to the incidence of major fatal accidents. In the Netlogo network world, the diffusion range is set to 3 grids.

(3) When $(\mathrm{d}U_1(t)/\mathrm{d}t) > 0$ and $(\mathrm{d}U_2(t)/\mathrm{d}t) > 0$, the growth rate of unsafe behavior income and the increase in cost, increase at the same time. However, the growth rate of income is greater than the growth rate of cost, which often leads to the incidence of serious accidents. In the Netlogo grid world, the diffusion range is set to 2 grids.

(4) When $(\mathrm{d}U_1(t)/\mathrm{d}t) < 0$, $(\mathrm{d}U_2(t)/\mathrm{d}t) < 0$, and $(\mathrm{d}U_1(t)/\mathrm{d}t) > (\mathrm{d}U_2(t)/\mathrm{d}t)$ at the same time, the growth rate of the unsafe behavior income and the cost growth rate are simultaneously reduced. Also, the growth rate of the income is still greater than that of the cost growth rate; such conditions are conducive to the incidence of minor injury accidents. In the Netlogo grid world, the diffusion range is set to 1 grid.

3.2.3. Supervision Agent Job Burnout Rules. The visual modeling editor creates a related submodel of the CMSS model based on the resource preservation theory; it monitors the agent's emotional resources as the research object and establishes interaction rules between the agents according to the relevant attributes of the CMSS submodel. The agent is free within the limits of the interaction rules.

(1) Emotional Exhaustion. For the state function of supervision, the emotional exhaustion state of the agent at time t is defined as the resource existence quantity, which is defined as R_t, and the comprehensive representation of each agent attribute in the CMSS model is as shown in the following formula:

$$R_t = R_0 - nR_c + S_c R_u + F_c R_f, \tag{9}$$

where n is the number of times the supervision agent handles illegal operations. When $R_t < 0$, the supervision agent will be exhausted, resulting in emotional exhaustion.

(2) Disintegration of Personality. The supervision agent's processing success rate for violation events can be expressed by the number of times a violation event occurs and the total number of violations handled, as shown in the following formula:

$$P_j = \frac{E_c \times n}{N}. \tag{10}$$

When the processing success rate P_j is less than the critical value, the supervision agent will evade the low-breaking violation behavior, and the miner agent will be in a state of alienation (personality disintegration), assuming that the critical value is P_0, as in the following formula:

$$P_j < P_0. \quad (11)$$

(3) Personal Achievement Status. Assume that the supervision agent is emotionally exhausted, and the processing success rate is lower than P_0; then, when the working state satisfies formulas (9) and (11), the supervisory agent's work frustration increases, and that agent's personal sense of accomplishment decreases.

3.2.4. CMSS Model Agent Interactive Rules. The CMSS model is implemented into the grid world based on the Netlogo simulation platform [35–37]. The movement of the model agent in the grid follows certain rules, as shown in Figure 4:

(1) When the moving range of the agent is set to 1, the moving range is the four grids in which the agent can move in one step
(2) When the moving range of the agent is set to 2, the moving range is 12 grids in which the agent can move in two steps
(3) When the moving range of the agent is set to 3, the moving range is 28 grids in which the agent can move in three steps
(4) When the moving range of the agent is set to 4, the moving range is 48 grids in which the agent can move in four steps

3.3. Validation of the CMSS Model. Validation verification is the core issue of simulation research [38–40]. The CMSS model is suitable for studying the optimization analysis of a mine safety supervision system, and it has strong practical applications. Its effectiveness verification includes theoretical verification and practical verification. The theoretical verification is carried out to verify the consistency between the CMSS model and the existing theoretical predictions. The practical verification is carried out to verify whether the simulation output of the CMSS model is consistent with the measured data from the mine. The theoretical verification of the CMSS model is completed by means of scientific literature and expert consultations. The surface CMSS model is found to be consistent with existing theoretical predictions. This paper verifies the practice of using the CMSS model with mine examples.

4. Example Analysis and Verification

Xinghai Yuanfa Mining Co., Ltd., is located on the north side of the main peak of Xinzhenan Mountain in the eastern section of Wahong Mountain, Ziketan Town, Xinghai County, Hainan Tibetan Autonomous Prefecture, Qinghai Province. Its geographic coordinates are longitude 99 degrees 35′03–99 degrees 35′38 and latitude 35 degrees 58′02 to 35 degrees 59′03. The mining area is more than 280 km away from Xining City, 140 km away from Gonghe County, where Hainan Prefecture is located, and 50 km away from Xinghai County. There is a sandstone road that extends along 262 km of National Highway 214 to another 22 km stretch of road that leads to the mining area, which implements the general manager responsibility system [41–43]. The enterprise consists of mining, mineral processing, tailings, auxiliary workshops, and other functional departments. It consists of five operational departments, one administrative (office) department and two workshops. The operational departments include the Production Technology Department, the Motor Supply and Marketing Department, the Finance Department, the Safety and Security Department, and the General Affairs Department. The administrative department is the office. The two workshops are the Mining Workshop and the Mining Site Workshop. The company organization is mapped to the CMSS model, according to the project process design and equipment configuration. The miner agent category includes 450 staff members, and the supervision agent category includes 60 staff members [8, 44]. According to the density of employees in the mining enterprise, the number of Netlogo grids is 100×100 for a total of 10,000 grids. A schematic diagram of a security management system for agent interaction based on agent interaction rules is shown in Figure 5.

According to the production quality and conditions of the project, the basic production operation of the mining enterprise adopts a discontinuous working system, that is, the annual production working day is 300 days. The main production process is 24 hours of continuous production, three shifts per day and 8 hours per shift. At present, the working system of 5 days per week has been widely implemented, and the attendance rate of mine producers is 95% [45, 46]. Although the enterprise has strengthened its safety supervision, there are still some security risks, as shown in Figure 6. Figure 6(a) shows that the miners do not wear safety helmets inside or outside the site. Figure 6(b) shows that the duty room is built underneath the umbrella rock. These examples of unsafe behavior and unsafe working conditions are the main causes of mine accidents [47–49].

4.1. Model Parameter Initial Value. The CMSS model stipulates that the miners' illegal operation frequency is 1 day and that such activity must occur after only one handover shift [50, 51]. According to source research of Yuanfa Mining Co., Ltd., the initial parameters of the model are shown in Table 1.

4.2. Simulation Research on Miner Agent Behavior Selection

4.2.1. Miner Agent Behavior Choice under Reward Strategy. The mining enterprise rewards miners for safe operations over a certain period of time. According to the safety performance income formula, R_1 is an important part of the safety performance income, which indirectly affects the operator JSA. The value $R_1 = 20$ is run to obtain Figure 7(a); then, the value $R_1 = 40$ is run to obtain Figure 7(b); and finally, the value $R_1 = 60$ is run to obtain Figure 7(c).

Figure 7(a) shows that when $R_1 = 20$ and $\text{JSA} = 3.9$, the safety behavior curve converges to 226, and the unsafe

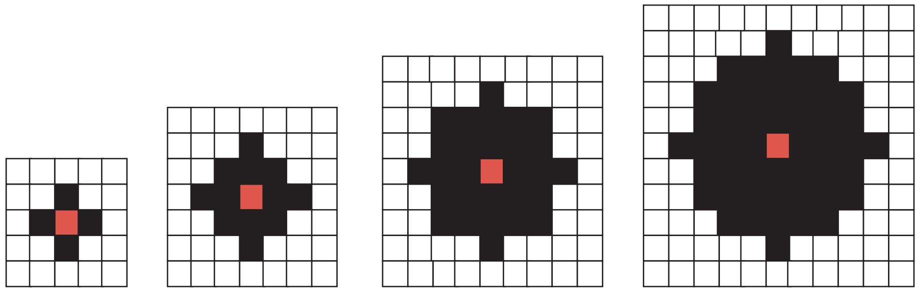

Figure 4: Schematic diagram of the agent's moving range.

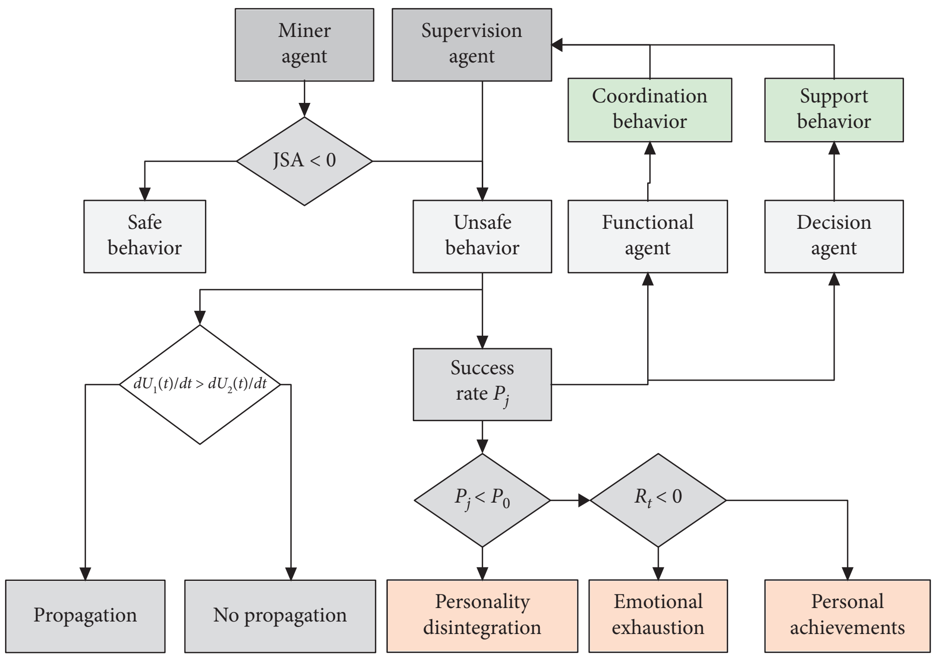

Figure 5: Schematic diagram of interaction rules of the safety management system.

(a) (b)

Figure 6: The current situation of unsafe behavior in mining enterprises.

Table 1: Initial parameter settings.

Parameter attribute description	Initial value	Parameter attribute description	Initial value
Miner impact range P_1	2	Duration of illegal operation T_c	15 min
Violation of work is monitored by P_2	2	Intervention probability of unsafe behavior N_2	0.68
Monitor agent visual range P_3	3	Unsafe behavior, enterprise loss	20
The probability of choosing unsafe behavior N_1	0.35	Continuous working time N	8 h
Safety behavior cost C_1	14	Processing effectiveness factor E_c	0.8
Unsafe behavior cost C_2	15	Monitor agent resource intrinsic quantity R_0	40
Safety behavior benefit R_1	23	Resource processing consumption R_c	2
Unsafe behavior gain R_2	24	Superior support resources R_u	10
Unsafe behavior, body and mind valence W_1	11	Function coordination resource quantity R_f	10
Unsafe behavior time titer W_2	13	Event processing success rate P_j	65%
Fine M	4.5	Decision support coefficient S_c	0.6
Bonus O	10	Functional coordination factor F_c	0.8

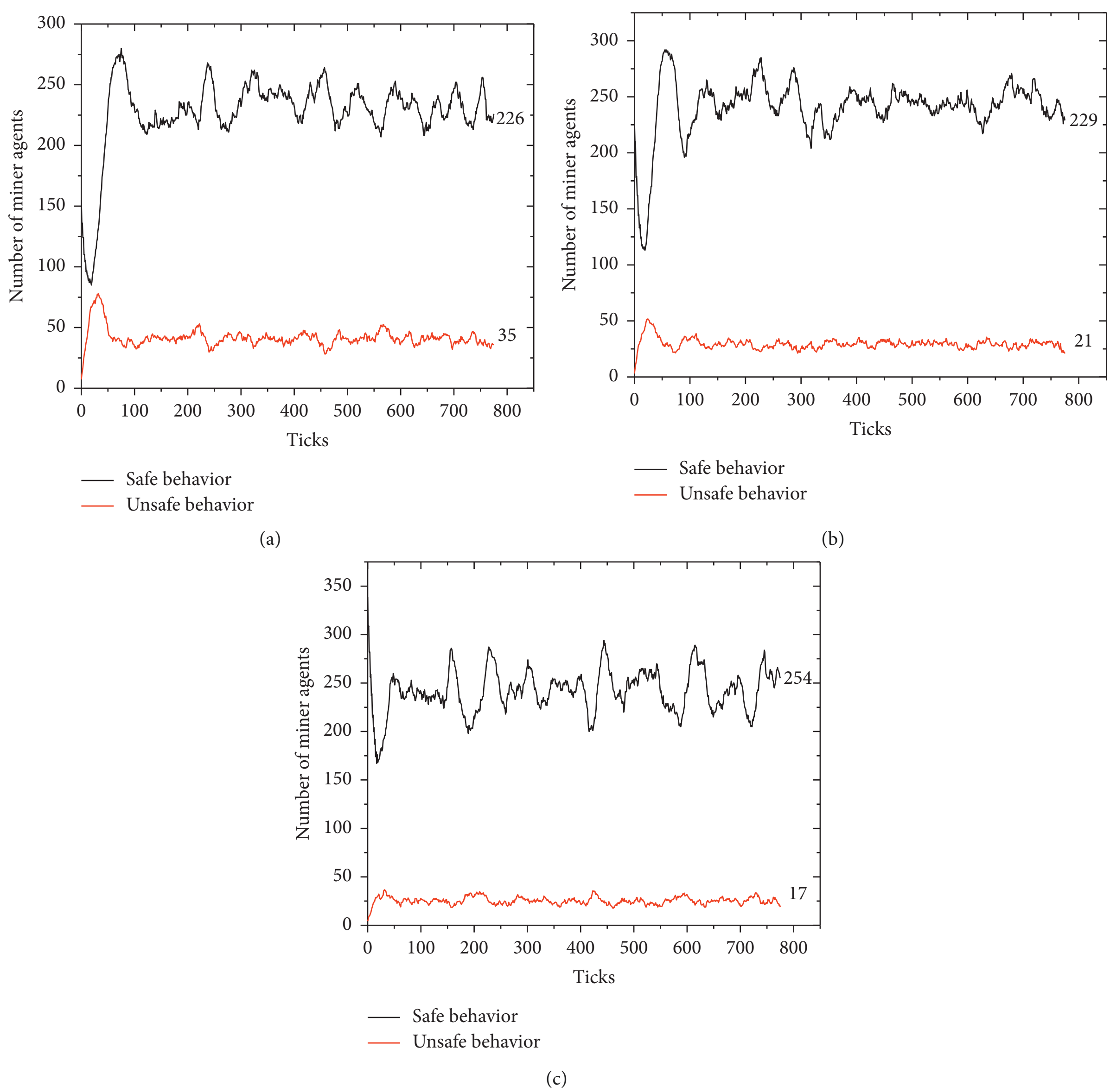

Figure 7: Impact of reward strategy on miner agent behavior selection.

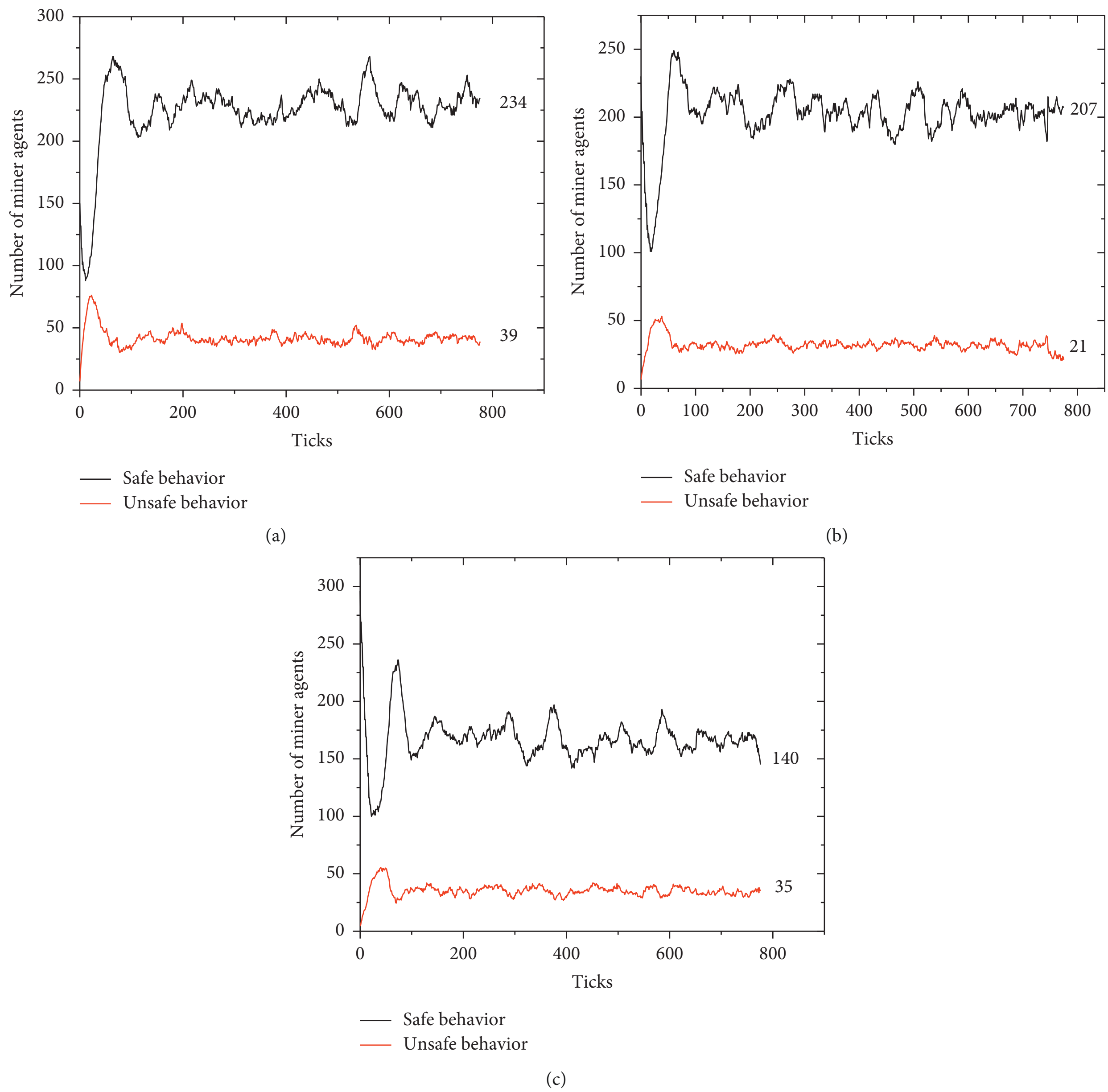

Figure 8: Impact of punishment strategy on miner agent behavior selection.

behavior curve converges to 35. Figure 7(b) shows that when $R_1 = 40$ and JSA = 5.02, the safety behavior curve converges to 229, and the unsafe behavior curve converges to 21. Figure 7(c) shows that when $R_1 = 60$, JSA = 25.83, the safety behavior curve converges to 254, and the safety behavior curve converges to 17. These results show that under the reward strategy, JSA increased by 21.93, the number of safe behaviors increased by 28, and the number of unsafe behaviors decreased by 18. The promotion of JSA under the incentive strategy promoted the choice of safe behavior by the miners.

4.2.2. Miner Agent Behavior Choice under Punishment Strategy. The supervision agent's intervention probability N_2 for the miner agent is set to 68%, and unsafe behavior cost $C_2 = 10$ is run to obtain Figure 8(a). Then, $C_2 = 20$ is run to obtain Figure 8(b). Finally, $C_2 = 40$ is run to get Figure 8(c).

From Figures 8(a)–8(b), we can see that JSA decreased from 1.12 to −1.26, the number of safe behaviors decreased from 234 to 207, and the number of unsafe behaviors decreased from 39 to 21. From Figures 8(b) to 8(c), JSA decreased from −1.66 to −6.02, the number of safe behaviors decreased from 207 to 140, and the number of unsafe behaviors increased from 21 to 35. These results show that the increase in punishment strategy causes JSA to decrease, penalty C_2 to increase from 10 to 20, and the number of unsafe behaviors and safety behaviors to be slightly reduced. However, when penalty C_2 is increased to 40, the spread of unsafe behaviors among workers led to a significant increase in the number of unsafe behaviors, while the number of safe behaviors decreased.

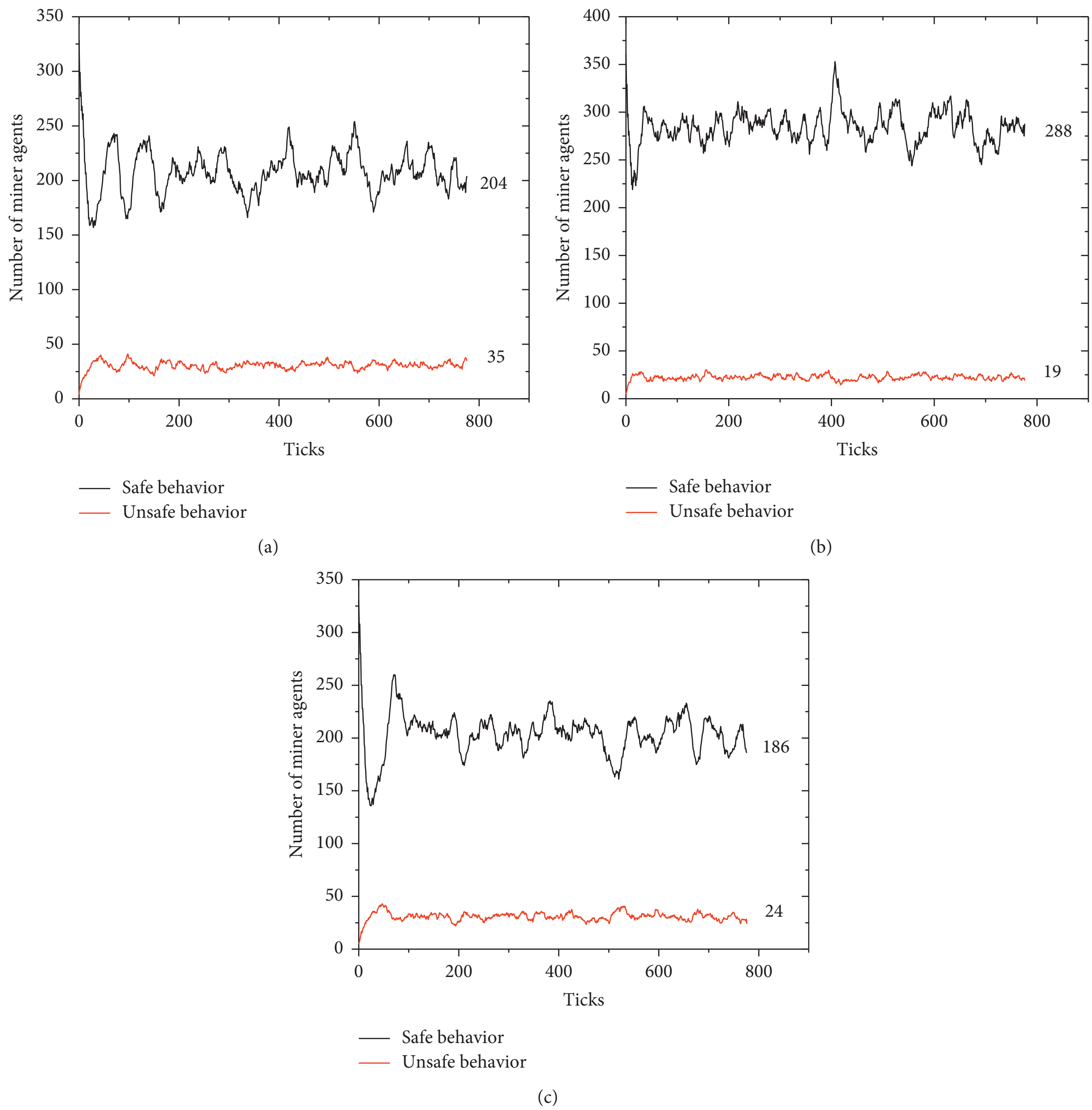

Figure 9: Impact of reward and punishment strategies on operator behavior choices.

4.2.3. Miner Agent Behavior Choice under Reward and Punishment Strategies. Generally, mining enterprises comprehensively consider reward and punishment strategies to constrain the behavior selection of miner agents. In the case of $R_1 = 20$, we first set $C_2 = 10$ to obtain Figure 9(a); we then set $C_2 = 20$ to obtain Figure 9(b). Finally, we set $C_2 = 40$ to obtain Figure 9(c).

In Figure 9(a), when $R_1 = 20$, $C_2 = 10$, and JSA = 16.9, the safety behavior number curve converges to 204, and the unsafe behavior number curve converges to 35. In Figure 9(b), when $R_1 = 20$, $C_2 = 20$, and JSA = 2.64, the number of safe behaviors increases to 288, and the number of unsafe behaviors decreases to 19. In Figure 9(c), when $R_1 = 20$, $C_2 = 40$, and JSA = −2.12, the number of safe behaviors is reduced to 186, and the number of unsafe behaviors rises to 24. These results, as shown in Figure 9(a), reveal that reward and punishment strategies combined with JSA result in the largest decrease in unsafe behavior choices. As penalties are expanded, JSA continues to decrease, and the effectiveness of reward and punishment strategies will also be reduced.

4.3. Simulation Research on Job Burnout of Supervisor Agent

4.3.1. Research on the Effect of Decision Support. By adjusting the decision support coefficient S_c to study its impact on-the-job burnout of supervision agents, as shown in formula (9), we see that S_c affects the supervisor agent's psychological resources R_t. First, $S_c = -1$ is run to obtain

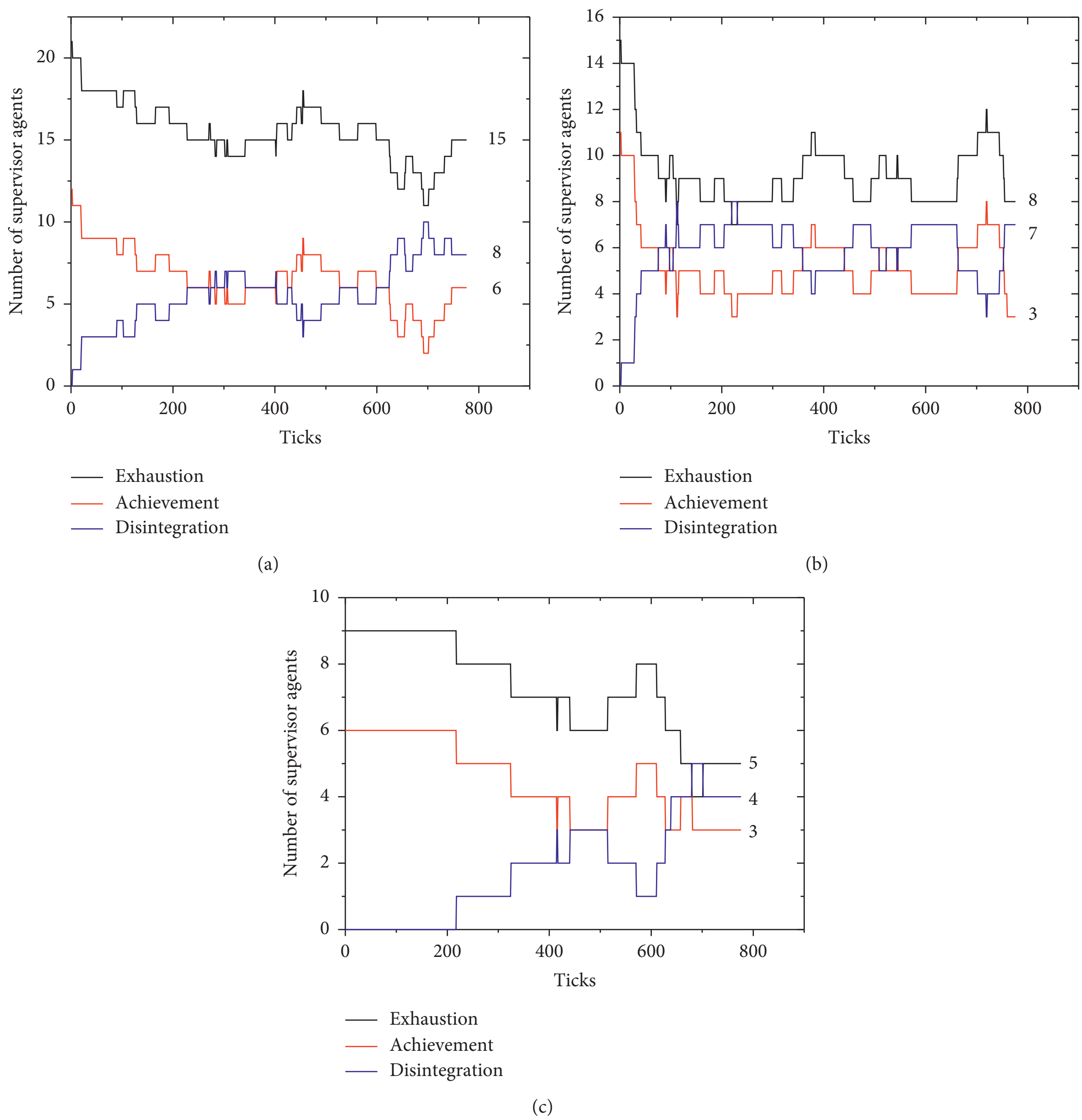

Figure 10: Impact of decision support on supervision agents.

Figure 10(a). Then, $S_c = 0$ is run to obtain Figure 10(b). Finally, $S_c = 1$ is run to obtain Figure 10(c).

In Figure 10(a), when $S_c = -1$ and $R_t = 22$, the number of people in the emotional exhaustion state is 15, the number of people who maintain the personality disintegration state is 8, the number of people who maintain personal achievement is 6, and the total number of supervisor agents who burnout is 29. In Figure 10(b), when $S_c = 0$ and $R_t = 32$, the number of people in the emotional exhaustion state is 7, the number of people who maintain the disintegration state is 8, the number of people who maintain personal achievement is 3, and the total number of supervisors who burnout is 18. In Figure 10(c), when $S_c = 1$ and $R_t = 42$, the number of people in the emotional exhaustion state is 5, the number of people who maintain the disintegration state is 4, the number of people who maintain personal achievement is 3, and the total number of supervisors who burnout is 12. These results show that the decision support coefficient S_c is positively correlated with R_t, and the increase in resource holdings alleviates the tendency for the supervision agent to burnout.

4.3.2. Research on the Effect of Function Coordination. By adjusting the functional coordination coefficient F_c to study its impact on-the-job burnout of supervision agents, as shown in formula (9), we see that F_c affects the supervision agent's psychological resources R_t. First, $F_c = -1$ is run to obtain Figure 11(a); then, $F_c = 0$ is run to obtain Figure 11(b). Finally, $F_c = 1$ is run to obtain Figure 11(c).

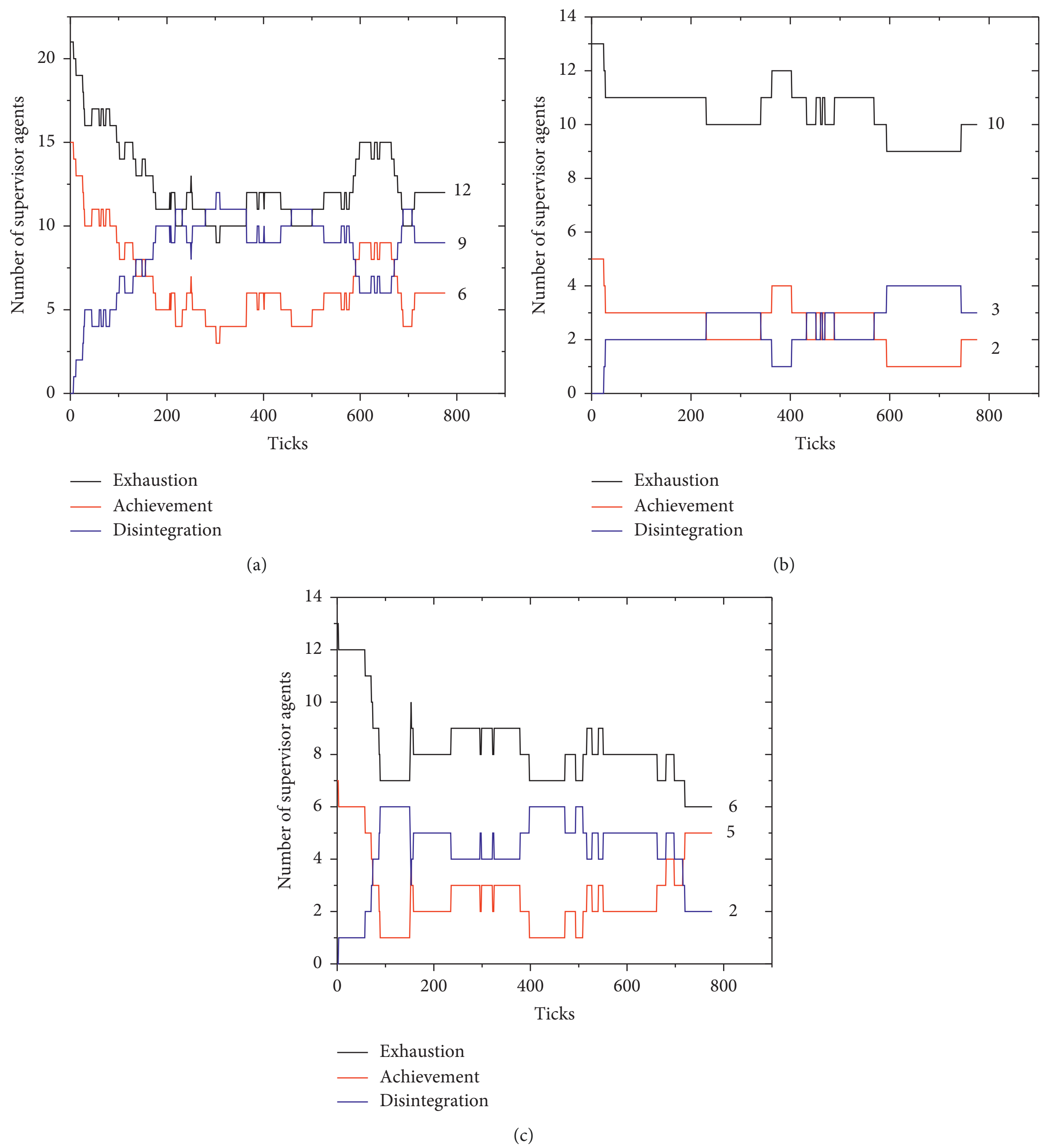

Figure 11: Impact of the degree of functional coordination on the supervision agent.

In Figure 11(a), when $F_c = -1$ and $R_t = 20$, the number of people in the emotional exhaustion state is 12, the number of people who maintain the personality disintegration state is 9, the number of people who maintain personal achievement is 6, and the total number of supervisors who burnout is 27. In Figure 11(b), when $F_c = 0$ and $R_t = 30$, the number of people in the emotional exhaustion state is 10, the number of people who maintain the personality disintegration state is 3, the number of people who maintain personal achievement is 2, and the total number of supervisors who burnout is 15. In Figure 11(c), when $F_c = 1$ and $R_t = 40$, the number of people in the emotional exhaustion state is 6, the number of people who maintain the personality disintegration state is 2, the number of people who maintain personal achievement is 5, and the total number of supervisors who burnout is 13. These results show that the functional coordination coefficient F_c is positively correlated with R_t, and F_c increases from −1 to 1. The statistic of supervision agent burnout is reduced from 27 to 13.

4.3.3. Research on the Effect of Miner Performance. By adjusting the processing effectiveness coefficient E_c to study its impact on-the-job burnout of supervision agents, as shown in formula (10), we see that E_c affects the supervision agent's success rate in handling violations. First, $E_c = 0.3$ is

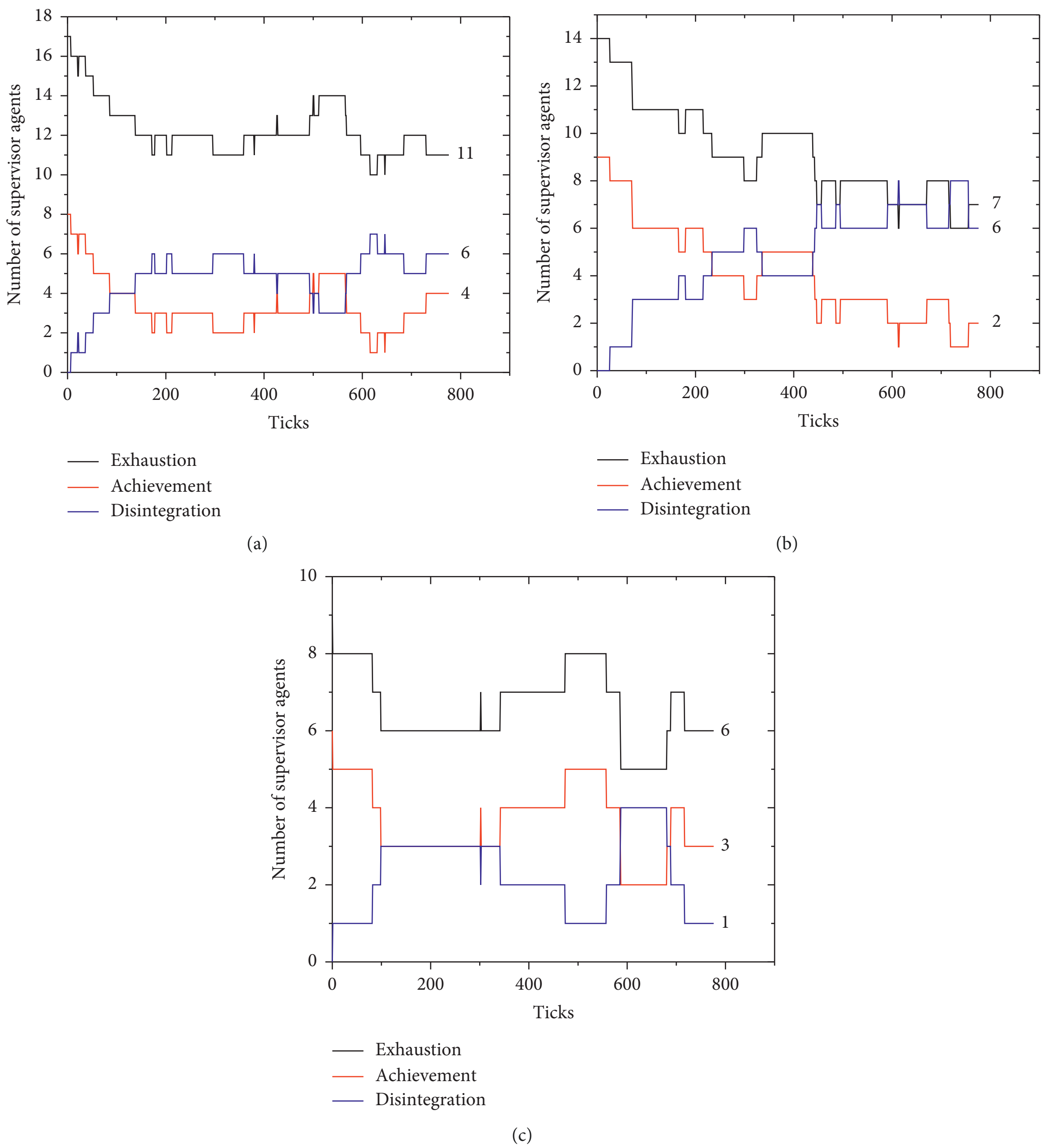

Figure 12: Impact of miner performance on supervision agents.

run to obtain Figure 12(a). Then, $E_c = 0.6$ is run to obtain Figure 12(b). Finally, $E_c = 0.9$ is run to obtain Figure 12(c).

In Figure 12(a), when $E_c = 0.3$ and $P_j = 24\%$, the number of people in the emotional exhaustion state is 11, the number of people who maintain the personality disintegration state is 6, the number of people who maintain personal achievement is 4, and the total number of supervisors who burnout is 21. In Figure 12(b), when $E_c = 0.6$ and $P_j = 48\%$, the number of people in the emotional exhaustion state is 7, the number of people who maintain the personality disintegration state is 6, the number of people who maintain personal achievement is 2, and the total number of supervisors who burnout is 15. In Figure 12(c), when $E_c = 0.9$ and $P_j = 72\%$, the number of people in the emotional exhaustion state is 6, the number of people who maintain the personality disintegration state is 1, the number of people who maintain personal achievement is 3, and the total number of supervisors who burnout is 10. These results show that when $P_j < P_0$, the number of supervision agents who burnout is higher, and when $P_j > P_0$, the number of supervision agents who burnout is lower.

4.4. Simulation Summary. The job situation adaptability is an important factor that affects the reward and punishment strategies. It is sorted by the job situation adaptability of

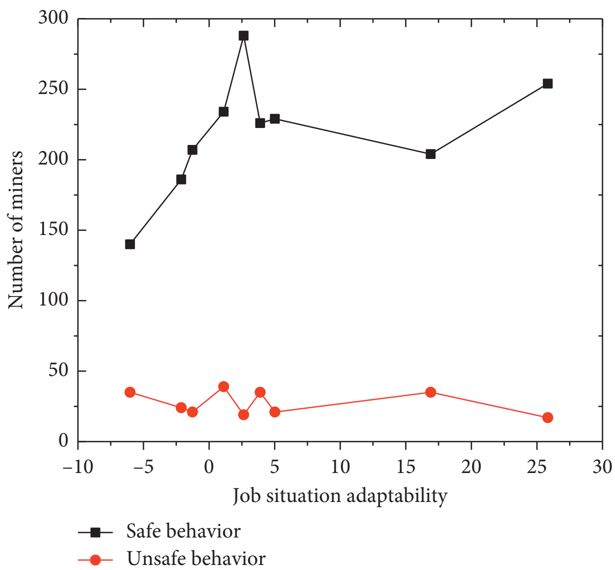

Figure 13: Miner agent behavior choice diagram.

Figures 7–9, drawing the miner agent behavior selection into a more intuitively discounted chart, as shown in Figure 13.

When JSA ∈ [−6.02, 2.64] ∪ [16.9, 21.93], reasonable measures are taken to guide the miners to choose safe behavior. When JSA ∈ [2.64, 16.9], increasing JSA indicates a decline in the number of safe behavior choices; at this stage, managers should adopt appropriate penalties to restrict unsafe behaviors and to increase the impact of reward and punishment strategies on the miners' behavior choices.

Simulation experiments based on the Netlogo platform show that under the influence of decision support coefficient S_c, when the number of S_c increases from −1 to 1, the amount of job burnout of the supervision agent is reduced by 17. Under the influence of the function coordination coefficient F_c, when F_c increases from −1 to 1, the amount of job burnout of the supervision agent decreases by 14. Under the influence of treatment effectiveness coefficient E_c, when E_c increases from 0.3 to 0.9, the amount of job burnout for the supervision agent decreases by 11. This indirectly indicates that the decision support coefficient S_c has the greatest influence on the supervision agent's job burnout, the functional coordination coefficient F_c has the second highest affect, and the processing effectiveness coefficient E_c has the least influence.

5. Conclusions

As an effective method for studying complex systems, ABMS can integrate computer science, sociology, economics, and management to examine multivariable nonlinear interaction phenomena in complex social economic organization systems. ABMS can be used to conduct analytical research on complex behaviors including punishment, rewards, and decision support. This paper combines ABMS technology and the conservation of resources theory to study the shortcomings of mine safety supervision systems. We construct the CMSS model and use the Netlogo platform to simulate the microbehavior of each agent in the mine safety supervision system. The CMSS model helps to make up for a lack of traditional qualitative analysis and an inability to systematically analyze the interaction among agents. By studying the macroscopic emergence phenomena caused by the interaction between agents in the safety supervision system, we provide a scientific basis for maximizing the utility of a mine safety supervision system.

The departments and types of work related to the safety supervision system of open-pit mining enterprises are more complex. Obviously, the more kinds of agents the simulation system contains, the higher the accuracy of the simulation experiment and the greater its reference significance. Future research should focus on the integrity and diversity of simulation data, and the characteristics of the agents should be more comprehensive and representative.

The CMSS model does not consider the relationship evolution and learning ability of each agent in the mine safety supervision system, so it has certain limitations. Further research should consider the learning ability of the agent and the process and mechanisms of the spread of unsafe behavior.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

Authors' Contributions

Xingxin Nie was involved in conceptualization, methodology, and software and formal analysis; Cunrui Bai carried out investigation, data curation, visualization, supervision, and writing; Jingjing Zhang supervised the study.

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