Research Article

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

Xing Xin Nie, Cunrui Bai, and Jingjing Zhang

School of Management, Xi’an University of Architecture and Technology, Xi’an, 710055 Shaanxi, China

Correspondence should be addressed to Xing Xin Nie; 670127529@qq.com

Received 14 July 2019; Revised 22 October 2019; Accepted 22 November 2019; Published 31 December 2019

Academic Editor: Sylwester Samborski

Copyright © 2019 Xing Xin Nie et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

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) ∈ [−6.02, 2.64] ∪ [16.9, 21.93], which uses a reward strategy to guide miners to choose safe behavior and (2) JSA ∈ [2.64, 16.9], which uses a punishment strategy to restrict unsafe behavior. The decision support coefficient $S_h$ 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 affects 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’ microbehavioral 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
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.

2.1.1. Environment Agent Properties

(1) The environmental location, that is, the size of the Netlogo simulation world is $100 \times 100$, 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:

$$K = 8 \sum_{j=1}^{n} \left(1 + i_j \right) + \varepsilon.$$  \hspace{1cm} (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 $\varepsilon$ is
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 $N_2$.

(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 the 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 the 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 $R_w$.

(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 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.

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:

\[
G_1 = N_{2t} \times (R_{1t} - C_{1t}) + (1 - N_{2t}) \times (R_{1t} - C_{1t}).
\]  

(2) T-Time JSA Function

\[
JSA_t = (1 - N_{1t}) \times G_{1t} + N_{1t} \times G_{2t}.
\]  

(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, is affected by JSA \( t-1 \) as follows:

\[
JSA_t = JSA_{t-1} + a, \quad JSA_t < 0,
\]

\[
JSA_t = JSA_{t-1} - b, \quad JSA_t \geq 0.
\]  

As shown in formula (5), when \( JSA_{t-1} < 0 \), after a shift in the mood, \( JSA_t \) will rebound to \( a \), resulting in a decrease in miners’ negative emotions. When \( JSA_{t-1} \geq 0 \), 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, is greater than 0, positive emotions begin to accumulate and suppress unsafe behavior, as shown in the following formula:

\[
JSA_t < 0, \text{IUB}.
\]  

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, The behavioral adaptive function mathematical expression is as follows:

\[
UBA(t) = [U_1(t), U_2(t), U_3(t), U_4(t), U_5(t)].
\]  

\( U_1(t) \) 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 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:

\( (dU_1(t)/dt) > 0 \) when the benefit of unsafe behavior increases gradually with time, the operator is more inclined to choose unsafe behavior

\( (dU_1(t)/dt) \leq 0 \) when the benefit of unsafe behavior is gradually reduced, the operator is more inclined to choose safe behavior.
Simulation data

Editor

U

and the JSA will gradually decline, thus creating workplace behaviors will be learned and imitated among the workers, growth rate of costs associated with unsafe behavior, unsafe come resulting from unsafe behavior is greater than the serious injuries, major fatal accidents, and major deaths: according to the degree of casualties: minor accidents, severe accidents, major fatal accidents.

Similarly, when \((dU_3(t)/dt) > 0\) and \((dU_4(t)/dt) > 0\), and \((dU_5(t)/dt) > 0\), the operator is more inclined to unsafe behavior, and when \((dU_6(t)/dt) < 0\), \((dU_7(t)/dt) < 0\), and \((dU_8(t)/dt) < 0\), the operator chooses unsafe behavior, and the probability is small.

Figure 3: CMSS model program architecture.

(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 JSA_1 > JSA_{i-1}, the probability of the operator selecting unsafe behavior will decrease; when JSA_1 < JSA_{i-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:

\[
\frac{dU_1(t)}{dt} > \frac{dU_2(t)}{dt}. \tag{8}
\]

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 \((dU_1(t)/dt) > 0\) and \((dU_2(t)/dt) < 0\), 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 \((dU_1(t)/dt) > 0\) and \((dU_2(t)/dt) < 0\), 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: \((dU_1(t)/dt) > (dU_2(t)/dt)\).

(2) When \((dU_1(t)/dt) > 0\) and \((dU_2(t)/dt) = 0\), 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 \((dU_1(t)/dt) > 0\) and \((dU_2(t)/dt) > 0\), 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 \((dU_1(t)/dt) < 0\) and \((dU_2(t)/dt) < 0\) and \((dU_3(t)/dt) > (dU_4(t)/dt)\) 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:

\[
R_t = R_0 - nR_c + S\times R_u + F\times R_f,
\]

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:

\[
P_f = \frac{E_x \times n}{N}. \tag{10}
\]

When the processing success rate \(P_f\) 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:

$$P_j < P_0.$$ (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 Xinzhen 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 35’02” 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 $100 \times 100$ 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 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.

Figure 6: The current situation of unsafe behavior in mining enterprises.
Table 1: Initial parameter settings.

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

Figure 7: Impact of reward 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.
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 $R_e$. First, $S_c = −1$ is run to obtain...
Finally, $S_c = 1$ is run to obtain Figure 10(c). In Figure 10(a), when $S_c = 0$ 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 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).
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
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
Figures 7–9, drawing the miner agent behavior selection into a more intuitively discounted chart, as shown in Figure 13.

When \( JSA \in [-6.02, 2.64] \cup [16.9, 21.93] \), reasonable measures are taken to guide the miners to choose safe behavior. When \( JSA \in [2.64, 16.9] \), 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.

### Acknowledgments

This work was supported by the National Natural Science Foundation of China (5197040521), National Social Science Foundation Project, China (18XGL010), and provincial and ministerial level-provincial philosophy planning office, Shaanxi Provincial Social Science Fund Project, China (2018S12).

### References

3. G. H. Ma, H. Qun, and S. Q. Zhu, “Research on the ways to overcome college counselors’ burnout guided by social cognitive career theory: taking Hunan University of Traditional


