Simulation and Analysis of Coal Mine Safety Escape Routes Based on a Multi-agent Model

Pan Lihu, Lu Feiping, Zhou Yaohui, and Qin Shipeng

***Abstract*—In order to discuss the influencing factors of mine escape decision when underground disaster occurs, this paper uses the multi-agent modeling theory to construct the coal mine safety accident escape model. The real escape scenarios of different chamber positions and multiple exits are simulated. Dijkstra algorithm was used for site selection and the shortest escape path is searched by combining breadth-first algorithm and adjacency matrix. The simulation results show that the multi-agent simulation modeling method has great advantages in simulating the evolution of complex systems.**

***Index Terms*—Breadth-first algorithm, coal mine safety, Dijkstra algorithm, multi-agent modelling.**

I. Introduction

In recent years, coal consumption has been on the rise. However, coal mining tasks are extensive and poorly managed, which leads to frequent accidents and casualties in the production process, as well as high costs for coal safety management. How to help miners save themselves when coal mine disasters occur is an important issue in coal mine safety management.

Currently, the problem of coal mine escape is mainly studied from two aspects. The first aspect focuses on coal mine safety from a qualitative perspective, such as in the studies by Jitendra Pandey *et al*. [1] and Wen Shen Wang *et al*. [2]. In the Jharia coalfields in India and coal mines in China, coal mine security, efficiency and sustainability have been studied considering the comprehensive factors that influence mine safety and corresponding evaluation systems. However, the evolution of coal mine fires under the influence of many factors has not been considered. The second aspect focuses on the spread of coal mine fires from a quantitative perspective, mostly with cellular automata and system dynamic (SD) methods. For example, Cherng-Shing Lin *et al.* [3] used a fire dynamics simulator (FDS) to simulate and analyze the reconstruction of fire scenes. This type of research generally focuses on static spatial equilibriums, involves fire development based on a quantitative index. However, the complex psychological factors and individual decision-making behaviors associated with coal mine escape are the important factors that are complex and cannot be ignored [4]. Therefore, it is important to study coal mine safety escape using computer technology to adopt appropriate modeling methods.

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Modeling and simulations based on multi-agent methods are effective ways of studying complex systems [5]. The basic elements of a coal mine system are regarded as simulation entities. All types of simulation entities can be described in the form of agents by building an agent-based model [6] (ABM) corresponding to a real-world situation. Taking Shaqu Mine of the Huajin Coking Coal Group in Shanxi Province as an example, a computer modeling method based on a multi-agent model is adopted to study the escape process in a complex coal mine system. The effects of the chamber design and multi-outlet arrangement on the escape of miners when a fire occurs are investigated.

II. Simulation Process and Rules

A. Modeling Process

The behavioral decision making and spatial environment change during coal mine escapes in a complex, dynamic and interactive process [7]. The distribution of chambers and exits and the escape decisions of various agents are the main factors that influence the ability of miners to escape. Different types of miner attributes may lead to different escape routes based on their age, familiarity with the environment and different escape decisions. The development of fires and the collapse of temporary obstacles can cause miners to reselect paths, and establishing multiple exits for chambers can increase the number of escape options. During the escape process, the miners will influence each other [8] and learn from each other, thus forming a multifactor-affected time-varying coal mine escape system. The escape process is modeled as a step-by-step calculation and updating method, as shown in Fig 1.

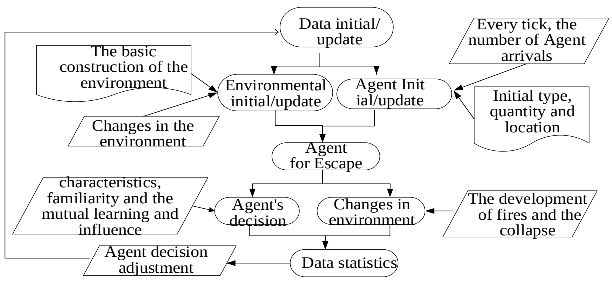

Fig. 1. Model operation flow chart.

B. Agent Type

1) Miner agents

1) Export-aware miners, who have a deep understanding of the exits and exit directions, are free from external influences, and quickly move toward an exit (as in formula 1).
2) Blind followers, who have no subjective initiative

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and follow the surrounding agents (for example, as in formula 2).

3) Environment perceptual miners, who have a clear understanding of the surrounding situation and the locations of the exits. In the process of reaching an exit, they can choose the node that requires the shortest time to reach (for example, as in formula 3).
4) Experience-rich miners, who can quickly predict the development trend of a fire and use the breadth-first algorithm to choose the shortest path.

2) Disaster agents

1) Fire agents, which encompass fires that spread along roadways.
2) Collapse agents, which encompass sudden roadway collapse events.

C. Agent Decisions

1) Miner agent decisions

a) Location selection

This paper uses the Dijkstra algorithm to search for the shortest path. When a miner begins to select a location, the model first excludes the invalid or nonexistent grid cells among the eight neighboring cells and then sorts the cells by distance to generate a grid sequence as the escape path of the miner. The corresponding formula is as follows:

$$S_{xy} = \min\sqrt{(x-x_n)^2 + (y-y_n)^2} \tag{1}$$

b) Direction selection

When their lives are in danger, miners often panic and subsequently follow the crowd. In the case of an emergency such as a fire, such a reaction is particularly common. In the fields of computer science and social science, this behavior is defined as large-scale group behavior. Therefore, in the mine escape strategy, direction selection is introduced to reflect the group behavior of the miners, and the escape process can accurately reflected with this approach.

There can only be one type of agent in each grid, namely, a fire, wall, or obstacle or miners. The first three are associated with invalid grid cells. That is, if one of these types of agent exists in a cell, miners will not consider the cell in the candidate path. The corresponding formula is as follows:

$$p_{(i,j)} = \frac{M_{(i,j)}}{\sum_{k=1}^{g} M_k} \tag{2}$$

where $p_{(i,j)}$ is the probability of the miners escaping through the grid cell with coordinates (i,j) in a certain direction, $M_{(i,j)}$ represents the current number of miners passing through the grid cell with coordinates (i,j), and $\sum_{k=1}^{g} M_k$ represents the number of miners in all grid cells in the Moore neighborhood at a given moment (excluding invalid grid cells). Thus, at a given moment, as the number of miners that pass through a grid cell in a given direction increases, the probability of this cell being selected in the escape path increases.

c) Adjacency matrix

In the coal mine roadway grid, we establish a weighted topology map $G(V,E)$, where V represents a collection of all the nodes in the roadway and E represents a collection of connected edges between roadway nodes. Thus, $E(G)=\{(u,v)\}$. In this geometry, each (u,v) represents an undirected edge between the fixed points u and v. The corresponding formula is as follows.

$$Edge[m][n] = \begin{cases} weight & \langle i,j\rangle \in E \\ 0 & \text{i=j} \\ \infty & \text{other} \end{cases} \tag{3}$$

First, we must establish two sets, D and T, based on the Dijkstra algorithm. The initial set of D is null, and the initial set of T is all vertexes. Then, in each step, the lowest-cost vertex in set T is transferred to D, and this process is repeated until the set of T is null. This process identifies the least-expensive escape route to an exit.

d) Breadth-first algorithm

Fires can rapidly spread along roadways. However, agents must predict the spread of a fire and choose the shortest path to an exit under the premise of avoiding the direction in which the fire is spreading.

In this model, the most difficult task is predicting fire development. When the model is run, all potential fire paths are identified and stored in map form; then, the shortest path is selected as the escape path of the miners through the breadth-first algorithm. This algorithm can effectively avoid fire cells and reach the exit in the shortest amount of time.

2) Rescue agent decisions

When a miner agent is blocked by fire and collapse obstacles, the miner cannot escape. As the fire spreads, the miner be burnt to death or suffocate. Therefore, the model determines an optimal chamber and multi-exit design for this situation. When the above situation occurs, the chamber will serve as a temporary evacuation site for the miner agent. Multiple exits can provide multiple paths for multiple agents. In other words, if one exit is blocked, a miner can escape through another exit. The establishment of chambers is related to the speed of mine escape. The following subsection describes the escape speed and establishment of chamber and multiple exit design rules. Because of the different ages and physical strengths of miners, the escape speed of miners will vary. The escape speeds of miner agents of various ages are shown in Table I.

TABLE I. RATE OF ESCAPE OF AGENTS AT DIFFERENT AGES

Age	25	30	35	40	45
Speed	3.17	3.11	3.06	2.95	2.89

In the escape process, there are many other environmental factors that indirectly affect the escape speed of the agent. The concentration of harmful gases and the concentration of oxygen will change with the development of the fire, and the impact on the escape speed will gradually decrease.

Therefore, the focus here is on the impact of smoke on the escape speed. According to the research of Frantzich and Nilsson, the escape speed of miners under smoky conditions can be expressed as follows [9].

$$V_s = \max\{0.1v_0, \frac{v_0}{c}(c+dk)\} \quad (4)$$

where V_s represents the miner escape speed under smoky conditions; c and d are fitting parameters equal to 0.706 m/s and -0.057m/s, respectively; and k is the extinction coefficient in the flue gas environment, which is set to 1.6 m. The average value in Table 1 is 3.06 m/s, and $V_s = \max\{0.306, 2.66\}$. Therefore, the value of V_s is 2.66 m/s.

e) Building chambers

In the escape process, it is inevitable that two situations will occur. First, the spread of the fire will block some escape routes. Second, the collapse of walls will change the escape options of miners. At such times, a chamber should be established as a temporary shelter for the miners so that the miners can reach the chamber for refuge in the event of an emergency. The chamber should be located on a main roadway so that it can be easily reached in all directions. The design distance can be expressed as follows:

$$L = a \times v \times t \quad (5)$$

where L represents the optimal escape distance from the miners to the safe haven; a represents the safety factor, which is set to 0.4; v represents the miner escape speed, which is 2.66 m/s based on formula 4; and t represents the safe escape time of the miner, which is set to 10 min. L is calculated to be 638.4 m in this case. Thus, within a safe escape time range, miners can move to the chamber to take refuge.

To explore the effect of chamber location on miners' escape, two methods are used to establish the chambers: One is to build according to the miner escape distance mentioned above so that the miners in the roadway are allotted the same rescue probability; and the other is to establish a chamber at the road junction to avoid blockages at the road junction.

f) Multi-exit agents

In the original single exit, once the exit is blocked by fire or temporary obstacles, the miners have little chance of escape. The addition of multiple outlet agents in this model is divided into two cases: one is to add multiple exits to the opposite side of the roadway and the other is to add multiple exits to the left side of the roadway to increase the path selection for unexpected situations.

III. Implementation of the Escape Model

A. Model Simulation Interface

The coal mine safety escape model is constructed using the Repast (Recursive Porous Agent Simulation Toolkit) simulation modeling tool and the Java language in the Eclipse development platform combined with ArcGIS, which is used to rasterize the geographic data and provide an operating environment for the model. Based on the Repast class library resources and ArcGIS map data processing function, the system development was completed.

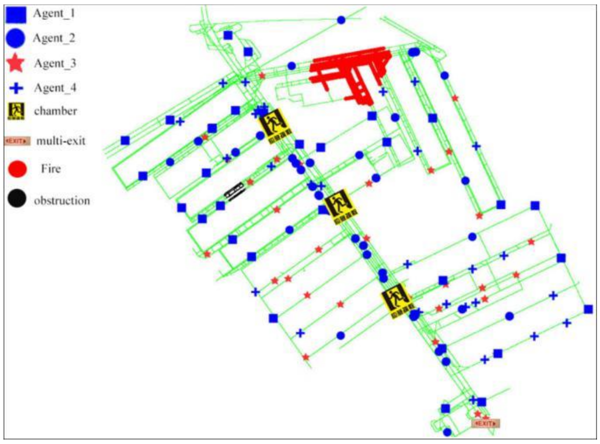

Fig. 2. Operating interface of the model.

The running interface of the model is shown in Fig. 2. The blue box at the top of the interface shows the toolbar of Repast, which provides the function of the controlling operation. The red box on the left side of the interface is the data control bar, which can adjust the program operation parameters. The pink box in the middle of the interface is the simulation operation interface, which includes miners, fire, temporary collapse and chambers. The green box on the right side of the interface is a statistical chart. The number of escapes of the miner agent when the model is running is displayed in the form of a line chart.

B. Model Operating Parameters

Many running parameters are included in the model and stored in a table according for each tick. The data generated in each tick can be updated in real time. Finally, the number of agents that die or escape to an exit can be obtained. According to the statistics and data analysis and the operating rules of the model, the miner decisions are adjusted to optimize the model and best reflect the actual situation of underground disaster avoidance. The values of the parameters in the model are shown in Table II.

TABLE II. Main Parameters in the Escape 2 Model Instance

type	name	value
Number	Agent_Num	100
Disaster	Fire	1 place
	Temporary collapse	1 place
Provide disaster relief	Chamber	3 place
	Multi-export	1 place
	Exit-aware	25%(ratio)
	Blind follower	25%(ratio)

Mine agent	Environmentally aware	25%(ratio)
	Experienced	25%(ratio)
Variable	Agent_Speed	3.06m/s
	Disaster_Exit	survey data

C. Architecture Design

The coal mine safety escape simulation model is divided into three phases: the simulation preparation phase, the operation phase and the data management phase. The simulation process is shown in Fig. 3.

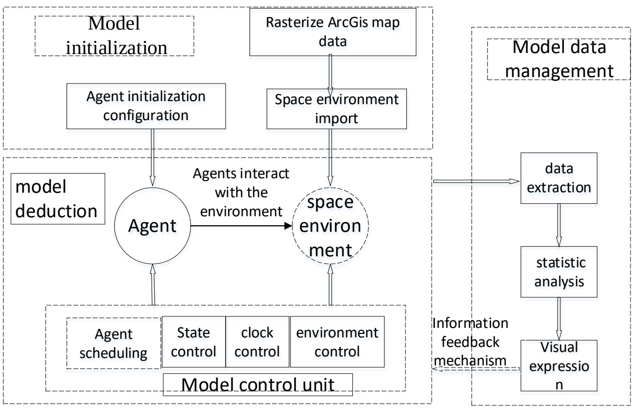

Fig. 3. Operation process for a coal mine safety escape simulation system.

The simulation preparation phase consists of two parts, namely, the introduction of the spatial environment and the initialization of the agents (miners, fires, chamber and temporary obstacles). The core of the coal mine safety escape model lies in the information interactions among agents and between agents and the environment [10]. Different types of agents and different individual agents are connected through information transmission [11] and follow a set of operating rules to determine decision behaviors and interact. The design of the module control unit ensures the normal operation of the system. This unit controls the execution sequence of each type of agent, identifies changes in the environment, and records and transmits data. The model results are extracted in the data management phase, statistically interpreted and displayed in the form of a chart.

IV. Simulation Results

A. Model Scenarios

In the coal mine safety escape model, the occurrence point of the fire and the location of the miners are randomly set up, which leads to the uncertainty of the experimental results. To solve this problem, 60 experiments were carried out for each scenario, and the escape and death data of the miners in each experiment were recorded and expressed in the form of charts. In addition, the escape process of the miners was combined to analyze the effect of the algorithm and the environment on the escape of the miners. Three change scenarios were selected in this study. The first type uses the position of the chamber as a change factor and establishes the chamber according to the miner's escape distance and the lane intersection to explore the impact of the chamber position on the safe escape of the miner. The second type uses multiple exit locations as a change factor, establishes multiple exits on the side and opposite sides of the roadway, and counts the escape numbers of various types of miners to explore the impact of multiple exit locations on safe escape. The third type combines two designs with a large number of escapes to verify the comprehensive impact of the establishment of the chamber and the establishment of multiple exits on the escape of the miners.

B. Results and Analysis

1) Simulation chamber position analysis

Fig. 4 and Fig. 5 shows that the number of people who were rescued by establishing a chamber by distance was higher than the number of people who were rescued by establishing a chamber by the road crossing. In the first 400 ticks, the number of rescued people increased greatly according to the situation in which chambers were established at the intersection of roadways. However, after 400 ticks, the number of people rescued decreased obviously according to the situation in which chamber were established at the intersection of roadways.

The analysis of the miner escape process showed that all the miners in the tunnel have the same chance to be rescued according to the distance design chamber; therefore, the number of rescued people in this scenario rises evenly. Setting a chamber at the intersection is conducive to the escape of the miners near the intersection; therefore, the number of miners escaping is greater in the first 400 ticks. However, in the subsequent 400 ticks, the miners far away from the intersection need more escape steps to be rescued; therefore, the number of people escaping in the later period of operation rises slowly. From an overall perspective, the number of miners escaping by the construction of chamber according to distance is greater than that in the other scenario; therefore, the establishment of chambers by distance is more conducive to miners' escape.

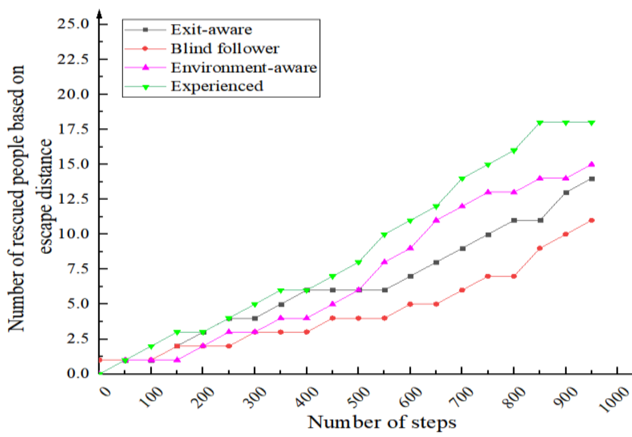

Fig. 4. Rescued based on chambers built by distance.

2) Simulation multi-export position analysis

Multiple exits are set up on the side and opposite sides of the roadway. The number of miners that escaped is recorded as shown in Fig. 6 and Fig. 7.

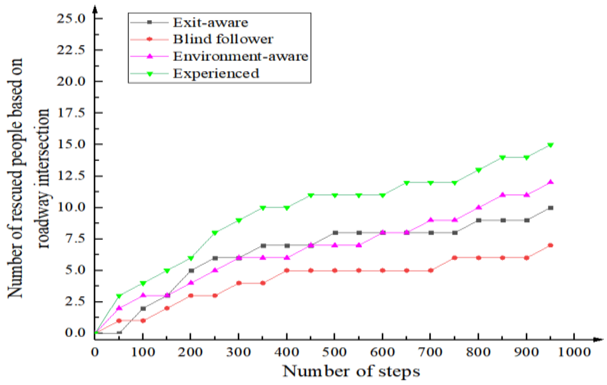

Fig. 5. Rescued based on chambers by lane.

A comparison between Fig. 6 and Fig. 7 reveals that in the case of setting up chambers on the side and the opposite side, the number of people rescued in the early stage increased by a large margin in the first scenario, while in the later stage, the rising margin gradually decreased. This trend is because miners near the exit can escape quickly in multiple exit situations, while miners farther away from the exit need more steps to escape safely.

Moreover, a higher number of escapes occur via multiple exits on the side than via multiple exits on the opposite side. And in terms of the number of escape steps, 980 ticks are needed to build a chamber, while 850 ticks are required to build a multi-exits on the side, miners require fewer steps to reach the exit on the side. Therefore, in this scenario simulation, it is reasonable to establish multiple exits on the side.

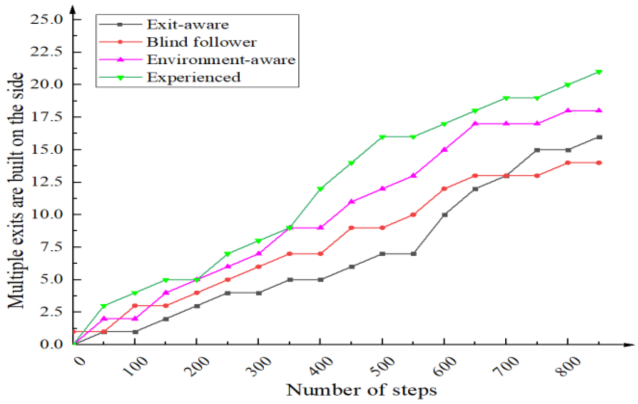

Fig. 6. Rescued people with multiple.

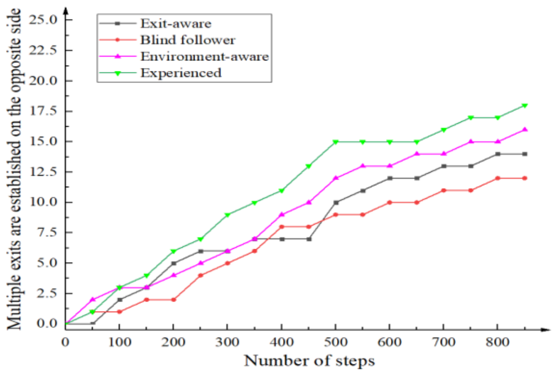

Fig. 7. Rescued people with multiple exits on the side exits on the opposite.

3) *Combined advantage analysis*

Through the above simulation of chambers and the multi-outlet analysis, a higher rescue rate of miners is observed by establishing the chamber by distance and establishing multi-outlets on the side. Therefore, the optimal cases are combined and the number of people rescued are shown in Fig 8. showing that by setting up chambers by distance and multiple outlets on the side, the rescue rate of all types of miners has improved. The total rescue rate reaches up to 86%, with 84% of the export-aware miners rescued, 76% of the blind entourage miners rescued, 88% of the environmentally aware miners rescued, and 96% of the experienced miners rescued. The escape rate of the miners can be improved based on the reasonable establishment of the chamber and multi-outlets positions during the construction of coal mine roadways. Moreover, the optimization algorithm can be used to avoid disasters and quickly find the shortest routes for miners to escape.

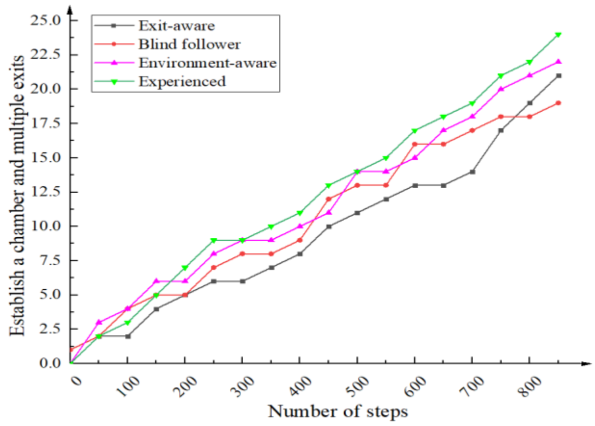

Fig. 8. People rescued with chamber and multi-exits.

V. Discussion and Conclusions

This paper constructs a multi-agent-based model of coal mine escape that is used to simulate four types of intelligent miner agents, namely, exit-aware, blind follower, environmentally aware and experienced agents, when a fire or temporary collapse occurs along a roadway. The escape process was assessed using different algorithms, a refuge chamber and multiple exits were established in different scenarios. The relevant escape and death statistics were obtained. The results indicate that the breadth-first algorithm can quickly identify the shortest path to an exit while avoiding the spread of fire. Establishing a chamber as a temporary shelter in an emergency situation due to fire, wall and roadway obstacles or establishing multiple exits not only reduces the escape time but also increases the number of potential escape routes. The simulation results show that the multi-agent simulation modeling method has great advantages in simulating the evolution of complex systems.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Pan Lihu designed the overall structure of coal mine safety escape, Lu Feiping designed the rules of all agents, and wrote the coal mine model code based on Repast, Qin Shipeng did data analysis and processing, Zhou Yaohui did basic data collection.

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