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A Cellular-Automaton Agent-Hybrid Model for Emergency Evacuation of People in Public Places

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ABSTRACT The importance of public spaces in the Chinese population is growing along with China's social and economic development. As a result, the potential for human casualties and economic loss if the emergency evacuation of public space is not timely and effective is also increasing. How to evacuate people from public places quickly and safely is the focus of current research in the field. This paper explores the role of people and the evacuation environment as factors that influence emergency evacuations. Then, an evacuation model is established using cellular automata and agent-hybrid theory. Matlab software is used to simulate the evacuation process of people from a school building in the event of a natural disaster, verifying the effectiveness of the model. At the same time, the model provides ideas for the formulation of relevant evacuation schemes.

INDEX TERMS Agent-hybrid, cellular automata, emergency evacuation, public places.

I. INTRODUCTION

Emergencies in public spaces in China have occurred frequently in the 21st century. On January 2, 2008, three firefighters were killed and 1,046 businesses were destroyed after a fire broke out at Dehui International Plaza in Urumqi, Xinjiang. The total economic loss reached 500 million. On September 27, 2011, there was a stampede after two trains collided on the Shanghai Metro Line 10. On December 31, 2014, there were 36 deaths and 49 injuries at the Shanghai Bund New Year's event. This series of events sounded an alarm for the Chinese population, demonstrating the social and political impact of emergencies. The evacuation of people in public places is an organic whole composed of many interrelated and interacting elements. It is a complex and large system with features such as complexity, multi-level, and feedback. As a place where people gather, once an emergency happens, if the evacuation is unreasonable, it often causes serious crowd casualties. Although some emergencies are unavoidable, the losses caused by them can be reduced if evacuations are better designed and managed. Therefore, the study on the evacuation of people in public places has important practical significance.

The psychology, physiology, and behavior of people are key factors determining the evacuation process. Therefore, in this paper, the superiority of the cellular automata model in the study of complex systems is taken into account. At the same time, the uncertainty caused by external and internal factors during the evacuation process of the people is considered, so agent-hybrid technology is considered to depict people's behavior to make the model description more accurate. To make different cell states, neighbors, and evolution rules work in unison in the entire system, the cells occupied by virtual people in cell space are regarded as agents, and the cells and their states are encapsulated and expanded to an autonomous agent, cell state as state attribute of the agent. By integrating the agent-hybrid into the cellular automata model and considering the decisions of individuals and the interaction between individuals and the environment during the evacuation process, emergency evacuation theory can be enriched and emergency evacuation plans for public places can be improved. Based on the observation of actual emergency evacuations and previous scholars' research of evacuation model theory and people's psychology, physiology and behavior, an emergency evacuation model for public places is established. Then the case of the successful evacuation of Sangzao Middle School during the Wenchuan earthquake is used to verify the validity of the model.

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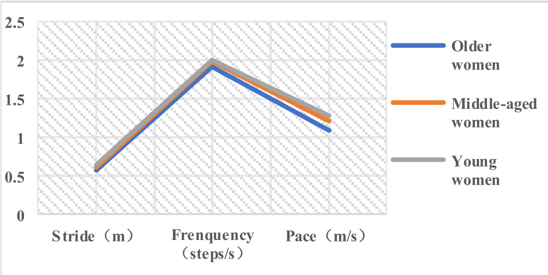

FIGURE 1. Movement of adult pedestrians of different ages in shanghai (Source: Shanghai Statistical Yearbook 2003).

II. LITERATURE REVIEW

Research on emergency evacuation of people first appeared in the 1960s. Givens discussed the general concept and framework of evacuation decision-making [1]. Since then, with the development of emergency evacuation theory, some achievements have been made in the study of emergency evacuation of people in public places at home and abroad. To study evacuation groups, Elzie *et al.* established an agent-based pedestrian movement model and found that groups played a significant role in spreading panic and that evacuation efficiency was affected by the size of the group [2]. Li *et al.* analyzed the factors affecting evacuations in subway stations from two aspects: individual characteristics of people and environment, and proposed a safety evacuation model for limited spaces. Then, A large number of experiments were used to explore the evacuation status at different facilities [3].

The cellular automata theory was first proposed by Von Neumann in 1951 and, since then, has seen ongoing optimization and improvement. The model's principles have been gradually applied to the study of the emergency evacuation behavior of people. For example, Kirchner, *et al.* proposed a system model based on the principle of cellular automata and studied the evacuation efficiency of a room with multiple exits under normal and emergency conditions respectively [4]. Based on cellular automata theory and agent modeling, Liu *et al.* established a passenger emergency evacuation model of a civil aviation aircraft considering the influence of the passenger physical characteristics during an emergency escape [5]. Fu *et al.* developed a multi-agent system based on a cellular automata model and then carried out an evacuation simulation considering the individual differences [6]. These pure cellular automata models have usually given less consideration to the characteristics of the subject itself and created rules based on the subject's movement behavior, which leads to the homogeneity of subjects. Therefore, to allow differences between subjects, other modeling methods, such as the agent-based modeling method [7], need to be used to refine the model. In recent years, the merging of features of cellular-automata and agent-hybrid models has gradually become a research hotspot, but there are also some problems in the construction of this type of model as well. In particular, the rules for setting the model are either too random or too rigid that they do not fit well with the real-life behavior of people. This problem has motivated the establishment of the model proposed in this paper: a model that, as much as possible, matches authentic human behavior as observed in research, and that further improves the cellular-automata agent-hybrid model combination to improve its simulation reliability.

III. ANALYSIS OF INFLUENCING FACTORS IN EMERGENCY EVACUATIONS OF PUBLIC PLACES

To determine the model parameters, the factors which influence the emergency evacuation process need to be identified and analyzed. Because the subject of the evacuation model is the person, a person's physiology, psychology and behavior will directly affect the evacuation result [8]. Such things as obstacles, facilities, and equipment in the evacuation environment also need to be considered.

A. PEOPLE FACTORS

People's evacuation behaviors reflect their own unique physiological and psychological characteristics and have a crucial impact on the evacuation process. Therefore, analyzing the influence of people factors is of great significance for emergency evacuation research.

1) PHYSIOLOGICAL FACTORS

The main physiological factors are as follows:

a: AGE

Age is an important factor that affects the functioning of the body. Its impact on people's evacuation behavior is mainly reflected in a person's discrimination, perception, reaction time, and speed of movement. The results of a 2003 study of adult pedestrians' walking speed by the City of Shanghai shows that, as age increases, pace, stride, and frequency decrease.

b: GENDER

In an emergency, men tend to respond more quickly and women more cautiously. When congestion occurs, men are more likely than women to take competitive actions to occupy a favorable position, while women are more likely to show panic and conformity. The pre-movement time of women is shorter than that of men [9]. Bryan, an American scholar, found that when a fire broke out, the first reactions of men and women were very different, as shown in Table 1 [10].

TABLE 1. First reactions of different genders in a fire.

First reaction	Female （%）	Male （%）	Standard error
Look for a fire extinguisher	2.80	6.90	1.77
Look for the source of fire	6.30	14.90	2.51
Evacuate from building	10.40	4.20	2.22
Call the police	11.40	6.10	2.41
Help others escape	11.00	3.40	2.22

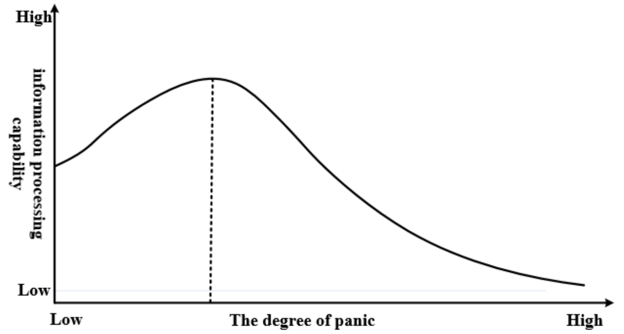

FIGURE 2. The relationship between information processing ability and the Degree of Panic (Source: safety psychology).

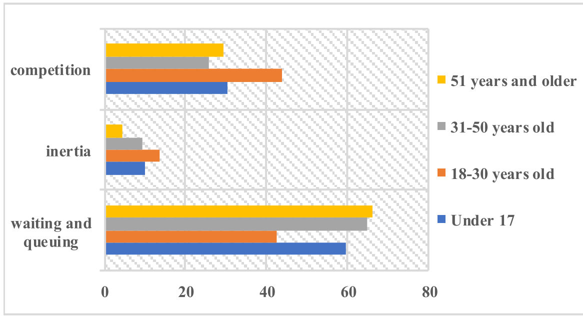

FIGURE 3. The relationship between information processing ability and the degree of panic.

c: DISABILITY

People with disabilities have more difficulty than able-bodied people in evacuations. The degree of difficulty increases with the level of disability. In this paper, the degree of disability is divided into ten grades according to China's occupational disease disability regulations.

2) PSYCHOLOGICAL AND BEHAVIORAL FACTORS

In an emergency, the amount of light, changes in temperature, sounds, smoke, odors, etc. will affect people's senses, cognitive ability, and behavior. In severe cases, they may not be able to make rational choices. An investigation of 22 people involved in the nine fires that occurred in Lubei District of Tangshan City in 2004 shows that 18 people (81.8 percent) were panicked and afraid and 4 people (18.2 percent) were able to stay calm and rational [11].

A review of relevant literature shows that the main psychological factors influencing emergency evacuation are:

a: PANIC AND FEAR

Due to the frequent complexity of public buildings and the suddenness of emergencies, people can experience severe stress and react with panic or fear [12]. Security psychology shows that nervousness can lead to panic and the decline of information processing ability (Figure 2). Subsequently, people can take inadequate action or overreact, resulting in secondary disasters such as stampedes and to further adverse effects on the evacuation and rescue of the whole group. Helbing *et al.* made a study on people in a panicked state and concluded that crowds in emergencies often want to escape from the disaster area at the fastest speed, resulting in blockages and stampedes at bottlenecks such as stairs and exits, which ultimately reduces the efficiency of the evacuation [13].

Wei Liu has identified the following behaviors of people aged 17 and over when they encounter a fire: waiting, queuing, competition, and inertia (Figure 3) [14].

b: CONFORMITY

Research shows that people tend to conform to the flow of people and choose the same escape route as others. Psychologists believe that conformity is due to herd instincts, the transmission of information between groups, and compensation. Incomplete, untimely, and ambiguous information can also prompt groups in emergencies to adopt conformity behavior. Conformity does not always hinder evacuation. Some scholars divide conformity behavior into three modes: universal conformity, rational conformity, and blind conformity. Rational conformity can help to optimize evacuation. The effect of blind conformity on evacuation is unpredictable, and in some cases, can even seriously hinder evacuation [15], [16].

B. EVACUATION ENVIRONMENT

Besides people factors, the evacuation process and its efficiency are affected by the environmental being evacuated [17], [18]. In this paper, environmental factors are divided into obstacles, facilities, equipment and children.

1) OBSTACLE FACTORS

Obstacles can be categorized as either fixed or movable. Fixed obstacles such as walls and pillars are normally avoided when people choose as an escape route. How people respond to movable obstacles such as furniture or depends on many variables such as the weight and size of the object. People familiar with the environment can usually avoid these obstacles and shorten their evacuation time.

2) FACILITIES AND EQUIPMENT FACTORS

Facilities and equipment for the evacuation of public places mainly include signs (visual and auditory) and lighting as well as fire extinguishing and smoke extraction systems. If facilities and equipment are inadequate or non-existent, evacuees may be unable to avoid obstacles or find an escape route, resulting in panic and non-adaptive behavior and subsequent dangerous consequences [19]. For example, if fire extinguishing or smoke extraction systems do not work well during a fire, flames and toxic gases may spread rapidly, harming people physically, impairing them mentally, limiting their vision and hindering the evacuation. Signs in public places can be divided into static and dynamic categories. The static category includes such things as indicator lights and guide signs. Dynamic indicators include broadcasts, alarms, and information provided by the staff on site. Well-designed static or dynamic indicators can help people choose the correct evacuation route, reduce unnecessary pathfinding behavior, and perform an evacuation quickly and safely.

3) WITH CHILDREN

If people are accompanied by children, the difficulty of evacuation will increase. When an emergency occurs, children are more likely to panic, so this requires the people to spend time to soothe the child's emotions. Besides, if a child is too young to escape independently, carrying a child will increase the load and increase the evacuation time.

IV. CONSTRUCTION OF EMERGENCY EVACUATION MODEL

A. EVACUATION MODEL TYPE AND ASSUMPTIONS

With the cellular automata model, the number of neighbors and the distribution settings will greatly affect the results obtained by the simulation. There are three common neighbor types, namely the Von. Neumann type, the Moore type, and the extended Moore type. The first neighborhood type (Von. Neumann) only has four directions: up, down, left, and right. People can only move in these directions, which is not in line with the walking directions of people in daily life, and the behavior of the neighborhood is only determined by the state of the four cells. Although the extended Moore neighborhood type is expanded, it also increases the range of cells to be considered at each time step, the calculation process is redundant, the program is relatively complicated, and its performance on people's behavior is also limited. Therefore, this paper will use the Moore type neighborhood. Suppose that:

(a) K people are randomly distributed throughout the public place in the initial state.

(b) After emergencies, people's evacuation always moves in the direction of the exit, and determines the next decision based on the surrounding environment and its own situation.

(c) In the process of people's evacuation, there will be psychological behaviors such as conformity, fear, panic, companionship, scrambling, helping, avoiding, and similar behaviors, as well as complex phenomena such as "Fool's haste is no speed".

(d) The evacuation speed is affected by personal psychological and physical factors and the environment. Different people have different evacuation speeds, and the evacuation speed of the crowd will determine the evacuation efficiency.

(e) In real scenes, people may seek refuge in safe areas of public places, which is not considered in this paper's model.

B. CONSTRUCTION OF CELLULAR-AUTOMATON AGENT-HYBRID MODEL

1) MODEL PARAMETER DEFINITION

The basic parameters are defined as follows:

(a) Cells: Cells move between cells to simulate the movement of people. Table 2 is the average size of the human body in different regions of China. Considering the maximum

TABLE 2. The average size of the human body in different regions of China.

	Region	Shoulder width (cm)	chest depth (cm)	Occupied area (m^2)
Male	Higher body area (Northeast, etc.)	44	20	0.19
	Middle body area (Ji, Lu, Liao, etc.)	41.5	20.1	0.17
	Lower human body area (Yangtze river delta, etc.)	41.4	20.5	0.17
Female	Higher body area (Northeast, etc.)	39	20	0.15
	Middle body area (Ji, Lu, Liao, etc.)	39.7	20.3	0.16
	Lower human body area (Yangtze river delta, etc.)	38.5	22	0.15

value of the average human body size, take the side length of each cell 0.5m.

(b) Occupied value: The attribute of the cell. Each cell may be occupied by a person. The occupied value is 1. It may be occupied by a fixed obstacle or impassable. The occupied value is greater than 1. Otherwise, it is empty, and the occupation value is 0. If the value of the cell is not 0, people cannot reach the cell.

(c) Coordinate values: (X_a, Y_a) represents the coordinate value of cell a, (X_b, Y_b) represents the coordinate value of obstacle b, and (X_c, Y_c) represents the coordinate value of exit c.

(d) Priority: P_a is the priority of cell a, which is used to describe the behavior of a person who tends to choose the nearest exit. When the physical and psychological conditions of the person are met and the person is familiar with the surrounding environment, the agent will choose the direction of the exit. In the evacuation space, the priority of each cell is $P\epsilon$ [0, 1], the priority of the exit is 1, and the calculation formula of the priority is as follows:

$$P_a = \frac{\sqrt{(x_{a^*}-x_{c^*})^2+(y_{a^*}-y_{c^*})^2}-\sqrt{(x_a-x_{c^*})^2+(y_a-y_{c^*})^2}}{\sqrt{(x_{a^*}-x_{c^*})^2+(y_{a^*}-y_{c^*})^2}} \tag{4-1}$$

In the formula,

c^* — — is the exit satisfying $min\sqrt{(x_a-x_c)^2+(y_a-y_c)^2}$

a^* — — is the cell farthest from exit c^*

At the same time, people always move in the direction from a small priority value to a large priority value.

(e) Congestion value: Use $T_c(a)$ to indicate the congestion degree of people from the initial position to the exit. The calculation formula is as follows:

$$T_c(a) = t_1 + t_2 \tag{4-2}$$

In the formula, t_1—— exit congestion value

t_2—— action congestion value

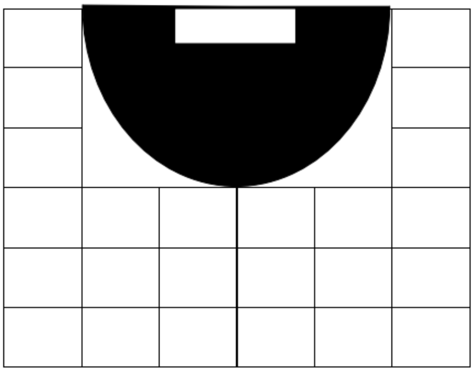

FIGURE 4. Exit congestion.

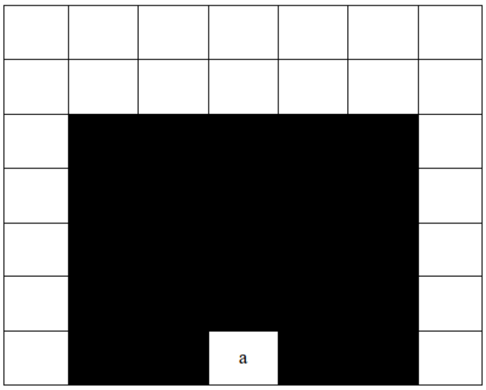

FIGURE 5. Action congestion.

Generally, an approximate fan-shaped congestion surface will be formed at the exit c.

$$t_1 = n_1/n_2 \tag{4-3}$$

In the formula, n_1——the total number of cells occupied by people near the exit with a crowed density greater than $2\ person/m^2$. n_2——approximate the number of rectangular cells formed by the tangent of the fan edge.

Without considering the backward movement of the cell, the cell a has 24 black cell neighborhoods in the direction of the exit c, and the occupied value of the cell occupied by someone or having an obstacle is 1, then

$$t_2 = f/24 \tag{4-4}$$

In the formula, f——the number of cells that occupied value is 1.

(f) Panic value: S is used to describe the degree of panic mentality of the people after the emergency. Let $S \in [1, 2, 3, 4, \infty]$, then S is set to 1 to indicate that the person is in an extremely panic state and cannot think rationally. The subsequent levels indicate that the degree of panic decreases in order.

(g) Familiarity: F is used to indicate the people's familiarity with the surrounding environment. Let $F \in [1, 2, 3, 4, \infty]$, then F is set to 1 to indicate that the person is extremely unfamiliar with the evacuation environment. Subsequent levels indicate decreasing familiarity.

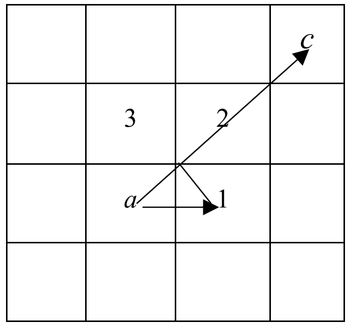

FIGURE 6. Schematic diagram of the inertial value calculation method.

(h) Conformity value: C is used to describe it. The conformity value of the cell will be dynamically updated with the evacuation process. The conformity value of the evacuation crowd increases when it passes through the cell, and decreases when it leaves, as follows:

a) Initial state: $C(a) = 0$.

b) When someone passed a in the previous round, the conformity value increase by $\Delta C = 1$.

c) When people leave, the formula for calculating the conformity value is:

$$C(a) = \frac{1}{S} \times \frac{1}{F} \times \left(\varepsilon C^{t-1}(a) + \Delta C\right) \tag{4-5}$$

In the formula, ε—— value is 0.5.

(i) Inertia value: I is used to describe it. As shown in Figure 6, person a is more familiar with the route leading to exit c, so he is more likely to choose the area that can quickly approach exit c. Therefore, the inertia value of cell a is the length of the projection of the line between cell a and cell 1 on the line between cell a and cell c.

(j) Instruction value: O is used to indicate that when there is an emergency evacuation organization to assist in evacuation, people generally follow their instructions to escape. The calculation method is the same as the inertia value, then multiply by a coefficient α. When there is an emergency evacuation organization, its value is taken as 1, if not, it is taken as 0.

(k) Attraction intensity: A is used to indicate it. the attraction intensity of a certain cell is determined by quantifying the above parameters. Meanwhile, it is assumed that the probability that a person chooses a certain cell as the direction of advance is proportional to the attraction intensity of the cell. At each round of operation, the attractive intensity of the eight cells around the human body must be calculated, and the next target point should be selected in descending order.

(l) Competitiveness value: E is used to indicate it, explaining the ability of people to reach the target point in the case of conflicting target points. The higher the value, the greater the advantage of successfully reaching the target point in a conflict. When the competitiveness of multiple people is not much different, one person is randomly selected according to the equal probability.

2) MODEL RUNNING RULES

The design model runs as follows:

(a) Determine the simulated public place, calculate the area of the place, divide into small square grids of size 0.5 * 0.5m, and estimate the maximum number of people to be evacuated.

(b) Each person can only move one space at a time and adopts the Moore type domain mode.

(c) Determine the attraction intensity of all neighbor cells of each person, and then select the corresponding cell as the target grid point for the next time step according to the result. When there are cases where the cell attraction strength is the same, the probability of selecting one of the targets is the same.

(d) Calculate the competitiveness value of each person. Each grid, that is, each cell, can only be occupied by one person or one obstacle. If there are cases where multiple people choose the same target point, they choose to stay with a large competitiveness value, and the rest return to their original positions. This can simulate the situation in which crowding and moving between people are difficult due to increased competition in a crowded area.

(e) People who have failed to compete remain in place. After excluding the original target point, continue to calculate the relevant values of surrounding neighbor cells, and choose the best one among them. If it continues to fail, continue to exclude the calculation until it reaches the next grid.

(f) Update the status of each person. If the person reaches the exit, exit the cycle. If other conditions occur, recalculate the corresponding indicators until all people are evacuated to a safe area.

(g) In addition, considering the possible psychological breakdown of people in the real evacuation situation, each person may have sluggish movements or stop the movement. Therefore, it is assumed that at each discrete time step, each person stays at the original position with probability P and moves with the probability of 1-P according to the above-mentioned operating rules.

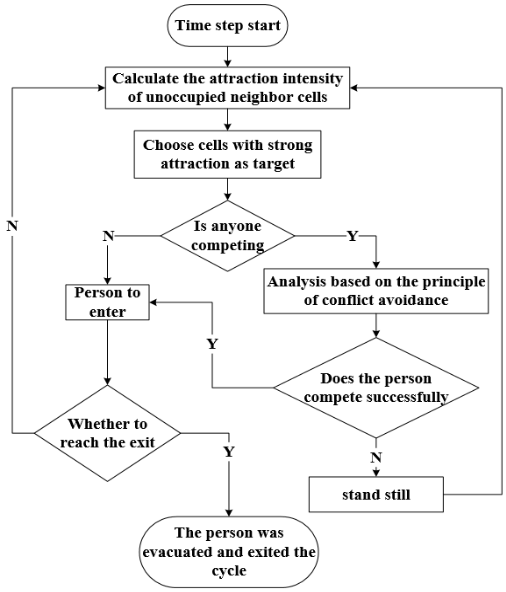

FIGURE 7. Model running process.

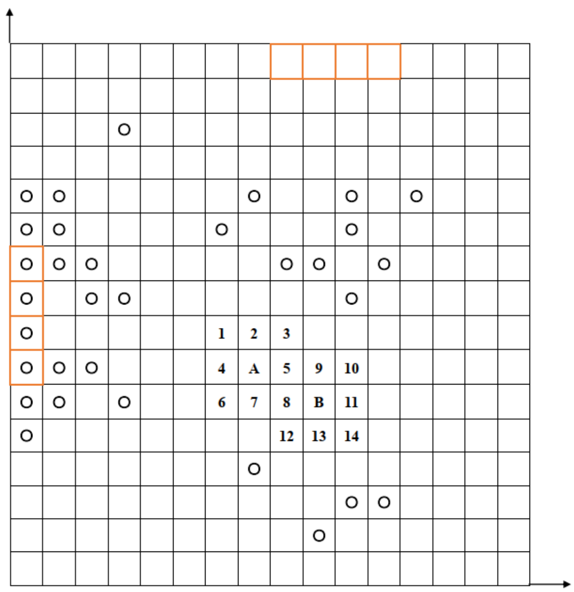

FIGURE 8. Example analysis diagram.

C. ANALYSIS OF MODEL EXAMPLES

After setting the model parameters and model rules, an example analysis will be used to explain the running process of the evacuation model, which can further understand the model.

As shown in figure 8, a rectangular two-dimensional space of 16 * 16 is set as the evacuation area, which includes the evacuation exit e_1 on the left and the exit e_2 above, as shown in the red border in the figure. The size is about 4 cells, that is, the width is 2m. People are represented by circles, and their distribution in the figure shows the distribution of people in the initial space. A and B in the box are the subjects of this study. The numbers 1 to 8 are the neighborhood of A, and the numbers 5 and 8 to 14 are the neighborhood of B.

Suppose A is familiar with the evacuation environment. The value of F_A is 4 and the exit e_1 is often used. When an emergency occurs, it is relatively calm, and the value of S_A is 3. B is very strange to the evacuation environment, and the value of F_B is 1, so there is no commonly used exit, and panic will appear during the emergency evacuation process. The value of S_B is 2. Continue to calculate other parameters as follows:

1) CALCULATION OF THE PRIORITY VALUE

Taking cell 1 as an example, the coordinate value takes the value of the center point of the square, and the unit is the number of squares. The exit e_1 is the closest exit to cell 1, and the coordinates of the exit e_1 are (0,8). The coordinate value of cell 1 is (6.5,7.5), and the coordinate value of the

TABLE 3. Calculation results of the priority value.

Cell point	Coordinates of cell a	Coordinates of the nearest exit c	Cell coordinates furthest from exit c	Priority P_a
2	(7.5,7.5)	(0,8)	(15.5,0.5)	0.563
3	(8.5,7.5)	(0,8)	(15.5,0.5)	0.506
4	(6.5,6.5)	(0,8)	(15.5,0.5)	0.613
5	(8.5,6.5)	(0,8)	(15.5,0.5)	0.499
6	(6.5,5.5)	(0,8)	(15.5,0.5)	0.596
7	(7.5,5.5)	(0,8)	(15.5,0.5)	0.541
8	(8.5,5.5)	(0,8)	(15.5,0.5)	0.485
9	(9.5,6.5)	(10,16)	(0.5,0.5)	0.477
10	(10.5,6.5)	(10,16)	(0.5,0.5)	0.477
11	(10.5,5.5)	(10,16)	(0.5,0.5)	0.422
12	(8.5,4.5)	(0,8)	(15.5,0.5)	0.446
13	(9.5,4.5)	(0,8)	(15.5,0.5)	0.412
14	(10.5,4.5)	(0,8)	(15.5,0.5)	0.357

cell farthest from the exit is (15.5,0.5), then:

$$P_1 = \frac{\sqrt{15.5^2 + (0.5-8)^2} - \sqrt{6.5^2 + (7.5-8)^2}}{\sqrt{15.5^2 + (0.5-8)^2}} = 0.621 \tag{5-1}$$

The priority values for the other points are shown in Table 3.

2) CALCULATION OF THE CONGESTION VALUE

$$T_{e_1}(A) = 16/32 + 2/24 = 7/12 \tag{5-2}$$
$$T_{e_2}(A) = 0 + 3/24 = 1/8 \tag{5-3}$$
$$T_{e_1}(B) = 16/32 + 1/24 = 13/24 \tag{5-4}$$
$$T_{e_2}(B) = 0 + 4/24 = 1/6 \tag{5-5}$$

From $T_{e_1}(A) > T_{e_2}(A)$, $T_{e_1}(B) > T_{e_2}(B)$, it can be found that the congestion degree of A and B going to exit e_1 is greater than that of exit e_2. Therefore, it can be known that A and B are more inclined to go to exit e_2 with less congestion. Therefore, the next goal of A and B will be to choose a neighborhood that can shorten the distance between A and exit e_2, where the distance between A and exit e_2 is

$$L_{A-e_2} = \sqrt{(10-7.5)^2 + (16-6.5)^2} = 9.823 \tag{5-6}$$

The distance between B and exit e_2 is

$$L_{B-e_2} = \sqrt{(10-9.5)^2 + (16-5.5)^2} = 10.512 \tag{5-7}$$

Then make

$$T_{A-e_2}(a) = \frac{(L_{A-e_2} - L_{a-e_2})}{max\left|L_{A-e_2} - L_{a^*-e_2}\right|} \tag{5-8}$$

In the formula —— the distance between A's 8 neighborhoods and the exit e_2, and the point with the largest difference from L_{A-e_2}.

It can be known from the formula structure that the larger the value, the easier it is for A to choose a as the next goal when considering congestion. The calculation of the congestion value is shown in Table 4.

TABLE 4. Calculation results of the congestion value.

Cell point	Coordinates of cell a	Coordinates of exit e_2	L_{a-e_2}	$T_{A-e_2}(a)$	$T_{B-e_2}(a)$
1	(6.5,7.5)	(10,16)	9.192	0.507	—
2	(7.5,7.5)	(10,16)	8.860	0.773	—
3	(8.5,7.5)	(10,16)	8.631	0.957	—
4	(6.5,6.5)	(10,16)	10.124	0.242	—
5	(8.5,6.5)	(10,16)	9.618	0.165	0.824
6	(6.5,5.5)	(10,16)	11.068	-1	—
7	(7.5,5.5)	(10,16)	10.794	-0.780	—
8	(8.5,5.5)	(10,16)	10.607	-0.630	-0.088
9	(9.5,6.5)	(10,16)	9.513	—	0.921
10	(10.5,6.5)	(10,16)	9.513	—	0.921
11	(10.5,5.5)	(10,16)	10.512	—	0
12	(8.5,4.5)	(10,16)	11.597	—	-1
13	(9.5,4.5)	(10,16)	11.511	—	-0.921
14	(10.5,4.5)	(10,16)	11.511	—	-0.921

TABLE 5. Calculation results of the inertia value.

Cell point	$I_A(a)$	Cell point	$I_A(a)$
1	1.131	5	0.992
2	0.141	6	0.849
3	0.849	7	0.141
4	0.990	8	1.313

3) CALCULATION OF THE CONFORMITY VALUE

It can be obtained from the formula that, for A, $C(1) = \frac{1}{3} \times \frac{1}{4} \times (0 \times 0.5 + 0) = 0$. Similarly, all of the other neighborhoods have a conformity value of 0 in the first round. For B, $C(5) = 1 \times \frac{1}{2} \times (0 \times 0.5 + 0) = 0$, so the other neighborhoods have a conformity value of 0 in the first round.

4) CALCULATION OF INERTIA VALUE

It can be known from the foregoing conditions that if A is familiar with exit the inertia value $I_A(a)$ can be calculated. The calculated inertia values at each point are shown in Table 5.

5) CALCULATION OF THE INSTRUCTION VALUE

Because exit e_1 is relatively congested, it is assumed that there is an emergency evacuation organization around it to direct and call on everyone to escape to exit e_2.

Then the inertia value of each cell point can be calculated by the same principle are shown in Table 6.

6) CALCULATION OF THE ATTRACTION INTENSITY

The calculation method of the attraction intensity is to add the calculation results of the above five indicators, and calculate the calculation results into a table, as shown in Table 7.

TABLE 6. Calculation results of the instruction value.

Cell point	$O_A(a)$	$O_B(a)$	Cell point	$O_A(a)$	$O_B(a)$
1	0.713	—	8	0.713	0.048
2	0.967	—	9	—	0.999
3	1.222	—	10	—	1.046
4	0.254	—	11	—	0.048
5	0.254	0.951	12	—	1.046
6	1.222	—	13	—	0.999
7	0.967	—	14	—	0.951

The next step for people to choose will be to consider the attractiveness of each neighborhood. As can be seen from the table above, the selection order of A is 3—1—2—4—5—8—6—7, and the selection order of B will be 10—9—5—12—13—11—8—14.

7) CALCULATION OF THE COMPETITIVENESS VALUE

In terms of personal physiological competitiveness, gender G is mainly considered. Among them, men take the value of 1 and women take a value of 0.7, which indicates the differences between men and women in strength, physical fitness, and psychological quality. Age is A. Physical health status B, where 1 is very healthy and 10 is physically disabled with the highest degree. In terms of personal psychology, the panic value S is mainly considered. In terms of the environment, the distance L between the starting point and the target point and whether to bring a child K are mainly considered. Among them, the value of with children is 0.4, and the value of without children is 0.

Then the formula for calculating the competitiveness value E is:

when $22 \geq A_{ge} \geq 0$

$$E = (G + \frac{A_{ge}}{18} + \frac{1}{H} - \frac{1}{S} - K)/L \qquad (5\text{-}9)$$

When $A_{ge} > 22$

$$E = (G + \frac{40}{A_{ge}} + \frac{1}{H} - \frac{1}{S} - K)/\text{L} \qquad (5\text{-}10)$$

Assume that the properties of A and B are shown in Table 8:

Then you can calculate A's competitiveness value for the next selection of cell 3 as:

$$E_A(3) = \frac{(1 + \frac{40}{30} + \frac{1}{3} - \frac{1}{3} - 0)}{\sqrt{2}} = 1.650 \qquad (5\text{-}11)$$

The competitive value of B for Cell 10 to be selected in the next step is:

$$E_B(10) = \frac{(0.7 + \frac{21}{18} + \frac{1}{2} - \frac{1}{2} - 0.4)}{\sqrt{2}} = 1.467 \qquad (5\text{-}12)$$

Because there is no conflict between A and B's next goals in this example, A can successfully reach Cell 3 and B can successfully reach Cell 10. If there is a situation of goal conflict between A and B in the future, it will mainly depend on the size of the competitiveness value. When the difference is less than 0.5, the arrivals will be randomly selected. When it is greater than 0.5, the party with the greater competitiveness value will successfully reach the goal point.

V. SIMULATION AND VERIFICATION

A. CASE DESCRIPTION

A sudden magnitude 8.0 earthquake in Sichuan in 2008 destroyed many buildings and killed many people. However, in the case of the Sangzao Middle School in a county, teachers, students and other building occupants were successfully evacuated to a safe area without any casualties. Among them, more than 700 teachers and students in the experimental teaching building were evacuated within 1 minute and 36 seconds. In this paper, simulation and verification are based on this background. Based on a large amount of data, the current evacuation environment can be restored as much as possible. After simulation with Matlab, the theoretical evacuation time obtained is compared with the actual evacuation time to verify the validity of the model.

Since some specific details of Sangzao Middle School are not available, it will be simplified when setting the environment. The main simulated scene this time is the experimental teaching building of the middle school. The building is a 4-story rectangular planar building. The four-story plan is shown in Figure 9. There are 16 classrooms, 4 classrooms on each floor, 2.1m wide corridor on each floor, and there are two staircases located between the classrooms. There is a door before and after the classroom. The width of the classroom is 6.6m, and the length is 9m, and the width of the door is 1.2m.

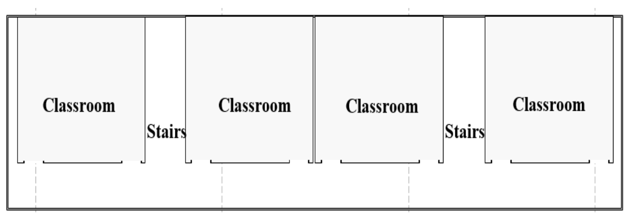

FIGURE 9. Four-story floor plan of the teaching building.

Sangzao Middle School held some evacuation drills before the earthquake. Therefore, it can be considered that teachers and students were basically familiar with the evacuation environment, but because they had not experienced real emergencies, they still have had varying degrees of panic, fear and other psychology when facing the earthquake. Middle school students are concentrated between 11 and 15 years old, and teachers are concentrated between 20 and 50 years old. Therefore, it is assumed that their average physical health is at least good. At the time of the earthquake, 11 classrooms were occupied, including 3 on the 1st, 2nd, and 4th floors, and 4 on the 3rd floor. Each class had 70 students and 1 or 2 teachers. Table 9 shows the parameters for assigning people in the evacuation.

TABLE 7. Calculation results of the attraction intensity.

Cell point	P_a	$T_{A-e_2}(a)$	$T_{B-e_2}(a)$	C_A	C_B	I_A	I_B	O_A	O_B	A_A	A_B
1	0.621	0.507	—	0	—	1.131	—	0.713	—	2.972	—
2	0.563	0.773	—	0	—	0.141	—	0.967	—	2.444	—
3	0.506	0.957	—	0	—	0.849	—	1.222	—	3.534	—
4	0.613	0.242	—	0	—	0.990	—	0.254	—	2.099	—
5	0.499	0.165	0.824	0	0	0.992	—	0.254	0.951	1.91	2.274
6	0.596	-1	—	0	—	0.849	—	1.222	—	1.667	—
7	0.541	-0.780	—	0	—	0.141	—	0.967	—	0.869	—
8	0.485	-0.630	-0.088	0	0	1.313	—	0.713	0.048	1.881	0.445
9	0.477	—	0.921	—	0	—	—	—	0.999	—	2.397
10	0.477	—	0.921	—	0	—	—	—	1.046	—	2.444
11	0.422	—	0	—	0	—	—	—	0.048	—	0.470
12	0.446	—	-1	—	0	—	—	—	1.046	—	0.492
13	0.412	—	-0.921	—	0	—	—	—	0.999	—	0.490
14	0.357	—	-0.921	—	0	—	—	—	0.951	—	0.387

TABLE 8. People's attributes.

People	Gender	Age	Physical fitness	Panic value	With children or not
A	Male	30	3	3	No
B	Female	21	2	2	Yes

TABLE 9. Evaluation parameters of evacuation simulation researchers in Sangzao Middle School.

Attribute	Variable	Proportion (%)
Gender	Male	42
	Female	58
Age	≤22	97
	> 22	3
Disability level	1	90
	2—4	7
	5—6	3
With children	Yes	3
	No	97
Environmental familiarity level	4	5
	∞	95
Panic level	1	43
	2	38
	3	11
	4	8

B. MODEL SIMULATION PROCESS AND RESULTS

Use Matlab software to program the rules of the basic parameters in the theoretical model, including functions and main program files, etc. When the main program file is run, related functions will be called, and the remaining trapped people and evacuation time output will be completed.

Because the size of the cell space was set to 0.5 * 0.5m in the previous paper, the size of the teaching building was adjusted to the following steps when the program was programmed: the door width was 1m, occupying 2 cell widths; the classroom width was 6.5m, occupying 13 cell widths; corridors are 2m wide, occupying 4 cell widths, etc. Then perform the initial settings according to the parameters of the above case. Suppose that the people randomly set the positions in the occupied classroom. After receiving the instruction when the earthquake occurs, they quickly gather toward the exit. The final running time results are shown in Figure 10, showing that in the case of the simulation of this model, it took 105.56s for all 781 people to escape successfully. The actual time for evacuating Sangzao Middle School was about 96s, the error value was about 9.56s, and the relative error was 9.96%.

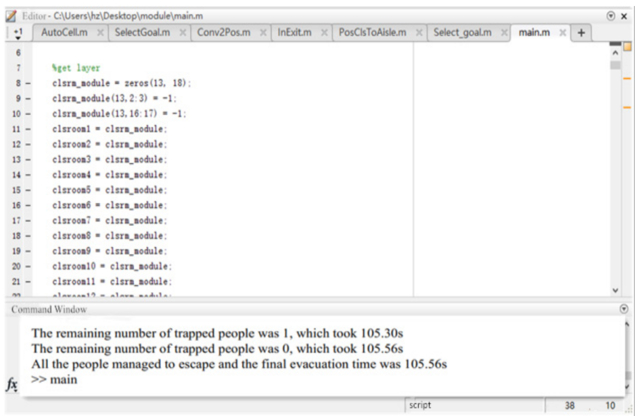

FIGURE 10. Evacuation results.

Compared with the simulation results of other evacuation models, the relative error between a pure cellular automata evacuation model and the measured data is 11.76%, and the relative error between the crowd dynamic evacuation model and the measured data is 23%. The simulation effect of the cellular-automaton agent-hybrid model is at a better level in the same type of evacuation model.

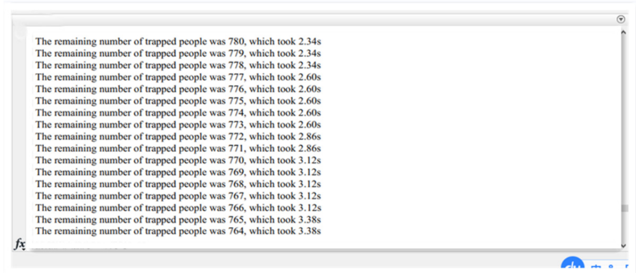

FIGURE 11. Evacuation time.

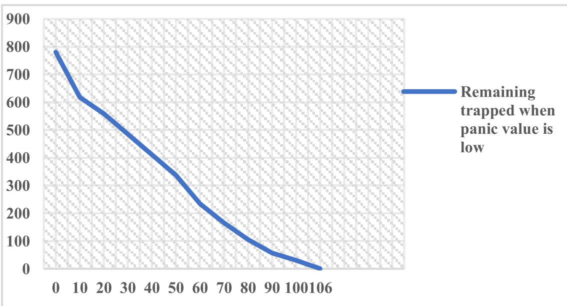

FIGURE 12. Remaining trapped people in different time periods.

In addition, when you see the evacuation of each person in the command line window of the program, as shown in Figure 11, within a short time of receiving the evacuation instruction, multiple people can escape from the exit at the same time step. With the passage of time, all students and teachers will gather towards the exit, thereby gradually forming a congested area near the exit, blocking the movement of people and decreasing the speed accordingly.

The evacuation time is divided according to a certain period and the remaining trapped people in each section are counted as shown in Figure 12. In the first 10s, the escape rate is relatively fast. This is because the evacuation path for teachers and students in class on the first floor is short, and the possible congestion areas they face are two exits at the front and rear of the classroom respectively. After the first wave of the earthquake, the teacher will issue an evacuation instruction. The front and back students close to the door will quickly move in that direction. However, due to the limited width of the door, a congested area near the door will be formed. The evacuation efficiency will decrease relatively, and the number of successful escapes per unit time will also decrease. For students above the second floor, the exit of the classroom is not the only point of congestion, and there are corridors and stairs, because all classes need to pass through these two passages, and the corridors and stairs are usually limited in space. In the case of crowds rushing to the passage, it may take more time to wait. At this time, the evacuation risk of teachers and students above the second floor will increase, and if the emergency is more critical, all escapes may not be successful. Therefore, it is necessary and urgent to fully study the emergency evacuation process, formulate emergency plans well in advance, plan evacuation paths, and provide evacuation guidelines to reduce congestion time.

VI. CONCLUSION

This paper focuses on the emergency evacuation of people in public places and explores the factors that affect the emergency evacuation process. Then, based on cellular automata and agent theory, the parameters of the model are abstracted, the model operation rules are set, and the evacuation model is established. A simple example analysis then illustrates how the model is used. Finally, Matlab software is used to simulate the case of Sangzao Middle School, which was successfully evacuated during the Wenchuan earthquake. The theoretical data obtained is compared with actual data to prove that the model is reasonable and accurate. At the same time, compared with other existing evacuation models, the cellular-automaton agent-hybrid model established in this paper takes into account the psychological, physical, and behavior of people and the interaction between people and the environment during the evacuation process. The relative error between the simulation result and the measured data is smaller, and it has better rationality and accuracy.

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