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A Fuzzy-Theory-Based Cellular Automata Model for Pedestrian Evacuation From a Multiple-Exit Room

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ABSTRACT The exit selection behavior of pedestrians plays an important part in the process of evacuation. This paper proposes a cellular automata model based on fuzzy logic method for simulating the evacuation of pedestrians from a multiple-exit room. When pedestrians select the exit, the distance and density are adopted as two important input variables in the fuzzy logic method, and the probability of selecting each exit is defined as the output variable of fuzzy logic method. The output variable of fuzzy logic, exit width and herding behavior are combined to determine the target exit. The competitiveness of each pedestrian is calculated by logit model to solve the position conflicts among pedestrians. The validation of the model is demonstrated by comparing the simulation data with the real data. The effects of attributes of pedestrians, exits and obstacles on evacuation are studied in simulations. Results show that large public facilities should control the inflows of pedestrians, and the reasonable increase of the exit quantity and exit width are effective for improving the evacuation efficiency. In the design of buildings, obstacles need to be designed reasonably, which should not be too large or too small. At the same time, obstacles should be kept at a certain distance from the exit, so as to ease the exit congestion and improve the evacuation efficiency. This paper takes the advantages of fuzzy logic method to solve the exit selection problem, which can effectively integrate the robustness with physiological-based ‘‘perception-action’’ behavior, the experience knowledge of pedestrians and the perception information of the surrounding environment into the decision-making process.

INDEX TERMS Cellular automata model, exit selection, fuzzy logic method, logit model, pedestrian evacuation.

I. INTRODUCTION

With the improvement of national urbanization, more and more large-scale public facilities have been built where people are easily gathered together, and crowd accidents are very easy to occur [1]. For example, on the night of December 31, 2012, 10 people including 4 children were killed, and 120 people were injured in a stampede at a stadium in Luanda, Angola. If the evacuation strategy is made in advanced, the accident should not have had such serious consequences. Therefore, the emergency evacuation of people has attracted the attention of experts and scholars all over the world.

At present, there are many methods such as conducting human experiments and developing pedestrian models to study pedestrian evacuation. Human evacuation experiments have been explored to some extent from the perspective of the effect of infrastructure layout, audio-visual ability on evacuation efficiency [2]–[7]. Although the results based on human experiments have made some progress, the cost of human experiment is very high in reality and some experimental scenarios are limited considering the personal safety

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of participants. Therefore, scholars begin to develop pedestrian dynamics models with the aid of computer technology to study pedestrian evacuation [8]–[12].

Generally, pedestrian movement model can be divided into the macroscopic model [13]–[17] and the microscopic model [18]–[23]. The macroscopic model which is described by flow, average speed and density usually regards the crowd as a homogeneous whole, and can well study the overall motion characteristics of pedestrian dynamics. The amount of computation when adopting the macroscopic model is relatively small. However, this kind of model usually ignores the detailed behavior and individual heterogeneity of pedestrians. Compared with the macroscopic model, the microscopic model focuses on the interaction between individuals, and the model types are more abundant including space-time continuous and discrete models. The common microscopic model refers to the social force model [24]–[28] that is based on Newton's second law, the queuing theory model [29]–[31] that is more suitable for describing pedestrian queuing and simulating bottleneck effect, and the cellular automata model that is often used to model complex systems [32]–[35].

The cellular automata model has been widely used, because it can represent some complex behavior characteristics such as self-organization phenomenon just based on simple rules. This paper, therefore, also adopts the cellular automata model as the basic motion model to study pedestrian evacuation in a multiple-exit room. The cellular automata model is a grid dynamics model. Wei-Guo *et al.* [36] used the improved cellular automata model to simulate the motion of crowd, and reproduced the arching formation, congestion and "fast is slow" phenomenon. Varas [37] simulated the effect of obstacles on pedestrian evacuation behavior based on the cellular automata model. Nowak and Schadschneider [38] studied the movement of bidirectional pedestrian dynamics with the aid of cellular automata model and proposed a prediction mechanism that can alleviate congestion. Tang *et al.* [39] simulated the process of queuing to enter a high-speed railway station with the cellular automata model. Zhou *et al.* [40] used the cellular automata model to study the influence of guidance information on pedestrian movement direction.

When pedestrians evacuate from a multiple-exit room, a strategic decision about exit selection should be made firstly. It is generally known that selecting an appropriate exit could not only make pedestrians arrive at the exit as soon as possible but also improve the whole evacuation efficiency. There are many factors that may influence the exit selection behavior such as distance, density, exit width. Cao *et al.* [41] proposed an exit selection method on the basis of utility theory, considering the factors of distance, density and visibility under the fire. Lo *et al.* [42] solved the exit selection problem relying on interactions between groups of pedestrians through adopting the game theory method. Mesmer and Bloebaum [43] further introduced Bayesian game theory into the exit selection model. Gao *et al.* [44] adopted the Logit method to determine the route by taking the distance factor and density factor into consideration. Liu *et al.* [45] and Fu *et al.* [46] also pointed out that the distance and density were two important factors to determine the selection of exit. However, the above mentioned methods for exit selection relied heavily on environmental information, and had high requirements on the accuracy of the distance and density information used. This paper takes the advantages of fuzzy logic method which can effectively integrate the robustness with physiological-based "perception-action" behavior, the experience knowledge of pedestrians and the perception information of the surrounding environment into the decision-making process to solve the exit selection problem. This advantage is very obvious compared with other methods that have been used before. Generally, "long" and "short" of distance, "big" and "small" of density are without clear boundaries due to environmental heterogeneity and subjectivity of human thinking. Therefore, the main contribution of this paper is that taking fully advantage of fuzzy logic method in imitating the fuzzy concept of human judgment to investigate exit selection problem.

Actually, the fuzzy logic method has been widely used in the field of crowd dynamics. Fu *et al.* [46] used fuzzy logic method to solve the pedestrian position conflict based on the pedestrian's physical state and familiarity with the environment. Zhou *et al.* [47] proposed a pedestrian movement model based on fuzzy logic method. Zhu *et al.* [48] developed a pedestrian evacuation model on the basis of fuzzy logic method. However, the above studies mainly used the fuzzy logic method to study pedestrian dynamics in a single exit room. The fuzzy logic method has not been used to investigate the exit selection behavior in a multiple-exit room which is also an important aspect of pedestrian evacuation research. This paper not only takes the distance and density as two key factors in determining the exit as [45], [46] do, but also considers the effect of exit width and the herding behaviors. Further more, the amount of computation by the use of the fuzzy logic method is reduced, and the robustness of selection behavior is better reproduced.

This paper is divided into four sections. The section I introduces the research background and innovation. In the section II, the cellular automata model used in this paper is introduced, exit selection method based on the fuzzy logic method and the confliction avoidance rules are proposed. In the section III, simulations are run based on the proposed model to study the relationship between evacuation efficiency and some influence factors. In the section IV, the conclusions are summarized.

II. MODEL DESCRIPTION

A. PEDESTRIAN MOVEMENT MODEL

In this paper, a cellular automata model with Moore neighborhood is used as shown in FIGURE 1(a). Each cell is either occupied by a pedestrian or empty and has eight neighbor cells except the boundary case. Pedestrians could move in

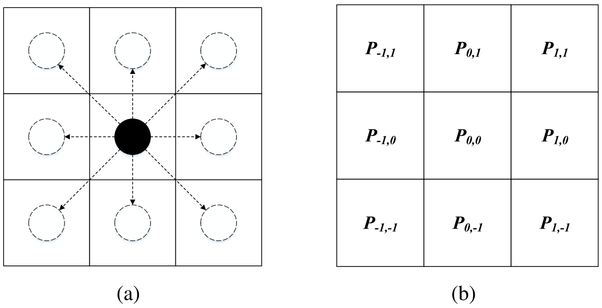


FIGURE 1. **Moore neighborhood: (a) the diagram of eight neighbor cells; (b) the nine probabilities for the pedestrian in the occupied cell to update his or her location.**

nine directions if the neighbor cells are all empty during the next time step as shown in FIGURE 1(b). The evacuation process ends when all pedestrians leave the room.

The movement direction of pedestrian is determined by the potential field value of the floor field. Floor field is divided into static field and dynamic field. Static field indicates the physical environment information that could be perceived by individuals. In this paper, the static field describes the attractiveness of different positions to pedestrians according to the distance to the target exit. The dynamic field is established on the basis of the route information of pedestrian movement, which reflects the pedestrian's herding psychology from the local perspective of movement model.

The position of cell is represented by (i, j). Set the static field $s_{i,j} = 1$ for the cell of exit. Set $s_{i,j} = 0$ for other cells. Moore cellular automata model is used in this paper [49]. For the neighbor cell (i, j) of center cell (i_0, j_0), if $s_{i_0,j_0} \neq 0$ and $s_{i,j} = 0$, $s_{i,j} = s_{i_0,j_0} + 1$. $s_{max} = max(s_{i,j})$, $S_{i,j} = s_{max} - s_{i,j}$. After traversing all cells in the flooring plant, the static field values of each position are obtained.

Set the dynamic field $D_{i,j} = 0$ for all cells. Whenever a pedestrian passes the position (i, j), $D_{i,j}(t + 1) = D_{i,j}(t) + 1$. Meanwhile, $D_{i,j}$ diffuses with α and decays with β, that is, $D_{i,j}(t + 1)$-$D_{i,j}(t) = \beta \Delta D(t) - \alpha D(t)$.

The calculation formula of pedestrian's transfer probability P_{ij} is shown in Eq. (1). Pedestrians would move to a neighbor cell with higher P_{ij} in the next time instant.

$$P_{ij} = \hat{N} exp(k_D D_{ij}) exp(k_S S_{ij})(1 - n_{ij}),$$
$$\hat{N} = [\sum_{i,j} exp(k_D D_{ij}) exp(k_S S_{ij})(1 - n_{ij})]^{-1}. \quad (1)$$

Here, K_D indicates the ability of identifying and mastering the path information left by other pedestrians. K_S indicates the influence of the surrounding environment and individuals. n_{ij} is used to determine whether a cell is occupied. $n_{ij} = 1$ if the cell is occupied by a pedestrian or an obstacle. Otherwise, $n_{ij} = 0$.

B. EXIT SELECTION METHOD

In the process of driving pedestrians to escape in a multi-exit room, pedestrians usually need to determine the target exit before moving based on the cellular automata model. Fuzzy logic method is used to simulate the exit selection behaviors of pedestrians in this paper. Generally, fuzzy logic method contains five portions, namely variable, fuzzification, rule base, fuzzy inference system and defuzzification [50].

In the process of applying fuzzy logic method, variables are divided into two types: input variable and output variable. The distance between the pedestrian and the exit "*dis*" and the density of pedestrians near the exit "*den*" are two factors that we used to determine the target exit, which keeps the same with that in [46]. The probability of selecting the exit "*pro*" is defined as the output variable.

After fuzzification processing, the variable is converted to the domain in a reasonable proportion. The fuzzy set of the first input variable (*dis*) includes "short", "middle" and "long" as given in Eq. (2) and FIGURE 2(a). The fuzzy set of the second input variable (*den*) includes "small", "middle" and "big" as given in Eq. (3) and FIGURE 2(b). The fuzzy set of the output variable *pro* includes "low", "middle" and "high" as given in Eq. (4) and FIGURE 2(c). It is noteworthy that Gaussian membership functions are adopted to describe the membership functions of the input variables and output variable in this paper. Besides, the maximum distance is defined as the diagonal length of the room. The maximum density is defined as the maximum number of pedestrians around the exit within a semicircle whose radius is 6 m.

$$\mu(dis) = \begin{cases} exp[-\frac{1}{2}(\frac{dis}{20})^2] \\ exp[-\frac{1}{2}(\frac{dis - 20\sqrt{2}}{10})^2] \\ exp[-\frac{1}{2}(\frac{dis - 50\sqrt{2}}{20})^2] \end{cases} \quad (2)$$

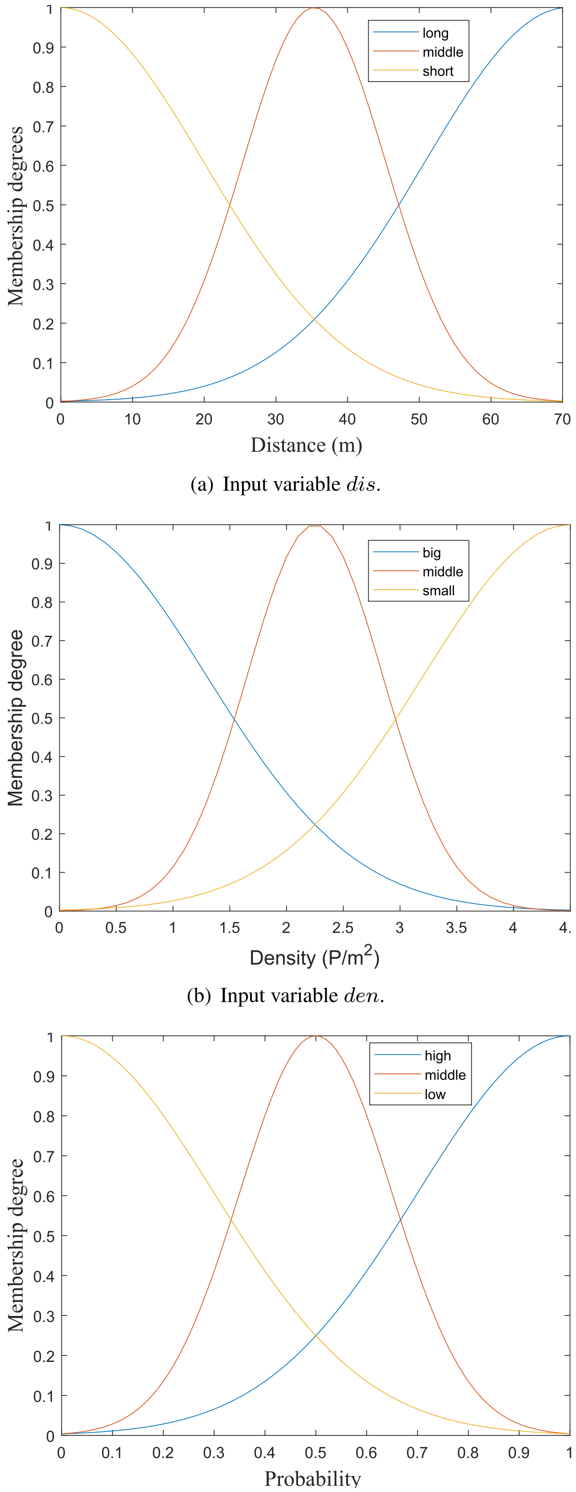
$$\mu(den) = \begin{cases} exp[-\frac{1}{2}(\frac{den}{1.3})^2] \\ exp[-\frac{1}{2}(\frac{den - 2.25}{0.6})^2] \\ exp[-\frac{1}{2}(\frac{den - 4.5}{1.3})^2] \end{cases} \quad (3)$$

$$\mu(pro) = \begin{cases} exp[-\frac{1}{2}(\frac{pro}{0.3})^2] \\ exp[-\frac{1}{2}(\frac{pro - 0.5}{0.35})^2] \\ exp[-\frac{1}{2}(\frac{pro - 1}{0.3})^2] \end{cases} \quad (4)$$

The rule base in TABLE 1 describes the strategies during the selection of exit, which could be realized by setting the input variables *dis* and *den*. Take the rule 6 as an example, it means that a pedestrian prefers to selecting an exit close to him with relatively low crowd density around the exit.

There are several aggregation methods in the fuzzy inference system, namely minimum, maximum, product, and summation [50]. In this paper, summation method is adopted because of its accuracy. The output variable (*pro*) equals to the summation of the outputs of each rule.

Through the process of defuzzification, the exact value (p^*) of selecting each exit is obtained. The most commonly used



(a) Input variable dis.

(b) Input variable den.

(c) Output variable pro.

FIGURE 2. **The membership functions of input variables and output variable.**

centroid defuzzification method is adopted in this paper given in Eq. (5).

$$p^* = \frac{\int_X x\mu(x)\,dx}{\int_X \mu(x)\,dx} \tag{5}$$

TABLE 1. **Rule base for the fuzzy logic method.**

Rule number	If-then statements
R_1	If dis is short, den is big, then pro is middle.
R_2	If dis is short, den is middle, then pro is high.
R_3	If dis is short, den is small, then pro is high.
R_4	If dis is middle, den is big, then pro is low.
R_5	If dis is middle, den is middle, then pro is middle.
R_6	If dis is middle, den is small, then pro is middle.
R_7	If dis is long, den is big, then pro is low.
R_8	If dis is long, den is middle, then pro is low.
R_9	If dis is long, den is small, then pro is middle.

where $\mu(x)$ is the membership degree of output variable (pro) and X is the fuzzy set of output variable (pro).

What we should pay attention to is that the exit width is also an important influence factor on exit selection behaviors of pedestrians. During the whole evacuation process, the exit width is a fixed value, so the width is not used as the third input variable when using the fuzzy logic method. In this paper, Eq. (6) is used to determine the probability of selecting each exit by combining both the exit width and the output variable *pro* of fuzzy logic method.

$$p_k^{\star} = \frac{\theta_k p_k^* e^{w_k}}{p_1^* e^{w_1} + p_2^* e^{w_2} + p_3^* e^{w_3}}, \quad k = 1, 2, 3. \tag{6}$$

$$\theta_k = \frac{e^{u_k}}{e^{u_1} + e^{u_2} + e^{u_3}}, \quad k = 1, 2, 3. \tag{7}$$

Here, w_k is the width of exit k and $p^{\star}$ is the final value that is used to select the target exit for the pedestrian, u_k is the number of pedestrians who choose the exit k as target in the pedestrian's vision field as shown in FIGURE 3. θ_k is the influence of u_k on the current pedestrian's selection, which reflects herding behavior from the perspective of global decision-making. In FIGURE 3, R indicates the vision radius, and ϕ represents the vision angle. According to [12], $\phi = 124°$. R is determined by the visibility of the environment. In this paper, we assume that $R = 4\ m$.

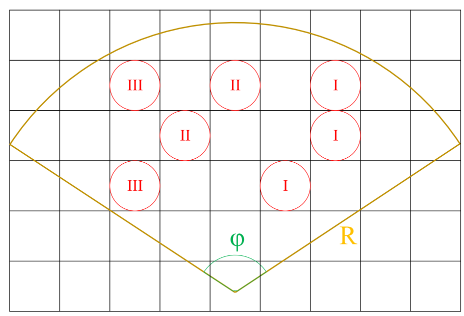


FIGURE 3. **Herding behaviors of pedestrians. "I", "II" and "III" are the different target exits of pedestrians in the vision field.**

C. CONFLICTION

When the density of pedestrians in an area is too high, multiple pedestrians will compete the same cell in the next time step. At this time, the most competitive pedestrian gets the position and moves, and the other two pedestrians need to redefine the positions. The corresponding three possible results of pedestrians in the next time instant in the state "a" are given in the states "b", "c" and "d". Actually, FIGURE 4 shows the rules to resolve the position conflict of pedestrians who have determined to select a certain cell "cc" as their targets in the next time step according to the rules in FIGURE 1. When determining the movement directions in the next time step, pedestrians could keep still according to the rules in FIGURE 1. However, it is also possible that the cell "cc" will be the next target cell for the surrounding three pedestrians according to the rules in FIGURE 1. The application premise of the rules reflected in FIGURE 4 is that these three pedestrians have determined to move to the cell "cc" according to the rules in FIGURE 1 in the next time step. The rule set in this paper to solve the position conflict is that the cell "cc" will be occupied by one of these three pedestrians in the next time step. Who finally could obtain the cell "cc" in the next time step will be determined by the value which is computed by Eq. (8). The physical state and the degree of willingness to compete are both considered in this paper. Generally, the stronger pedestrian is more likely to grab position. Besides, the pedestrian with stronger competitiveness is more conducive to occupying position. Logit model is used to calculate the competitiveness of pedestrians in position conflict as shown in Eq. (8).

$$c = \frac{e^{x_1} + e^{x_2}}{e^{x_1} + e^{x_2} + 1}, \quad (8)$$

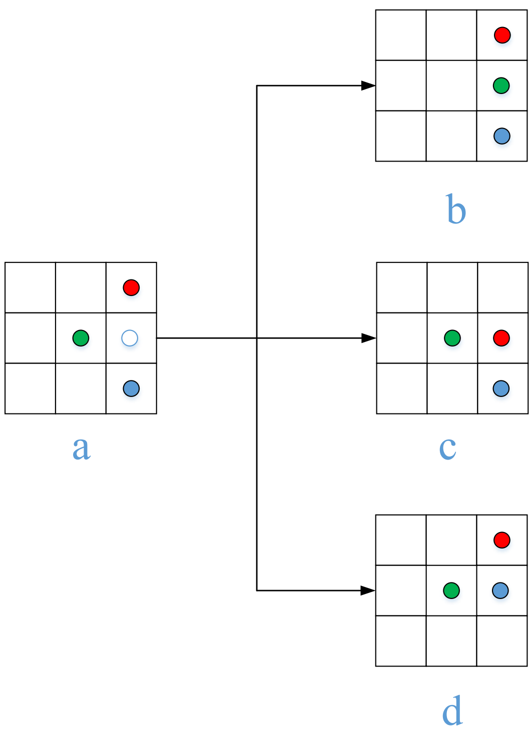


FIGURE 4. The states before and after a position conflict of pedestrians. "a" shows the initial states of pedestrians. The red, green and blue circles in the state "a" represent the pedestrians in competition, and the white circle in the state "a" represents the competitive position. "b", "c" and "d" respectively show different possible states after the conflict.

where x_1 is the pedestrian physical state, x_2 is the pedestrian competitiveness and c is the competitive power. x_1 and x_2 fall between 0 and 1, and they conform to the normal distribution. The pedestrian who has the maximum value of c gets the position.

D. UPDATE RULES

The fuzzy-theory-based cellular automata model updates according to the steps in FIGURE 5.

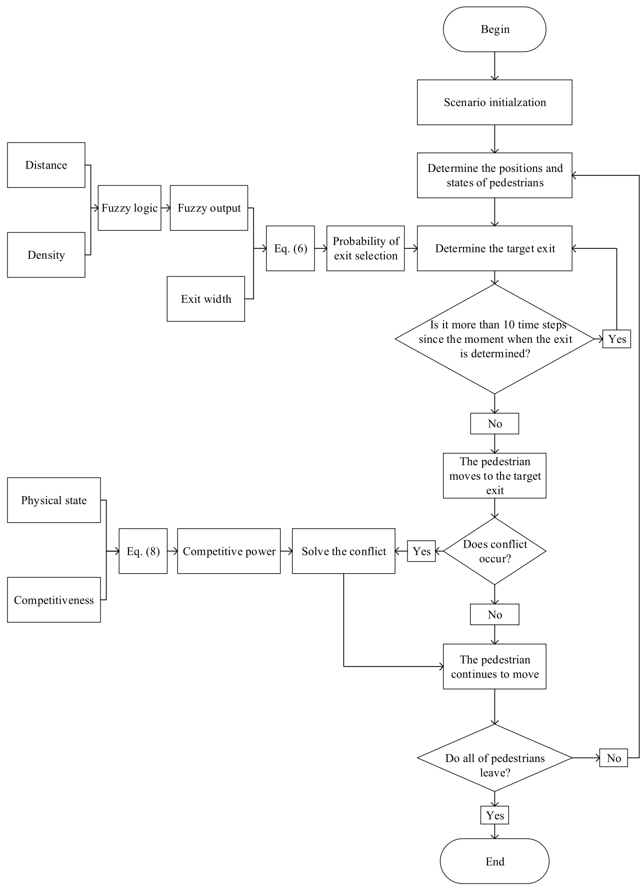


FIGURE 5. The flow chart of the update rules of pedestrian evacuation.

Step 1: Set the initial positions and states of pedestrians. Set parameters x_1 and x_2 for each pedestrian. Both of them follow the normal distribution.

Step 2: Determine the target exit by calculating the variable $p^{\star}$ by Eq 6.

Step 3: The pedestrian moves to target exit according to the cellular automata model expressed by Eq. (1).

Step 4: Determine whether existing conflicts for the same position. If it does, solve the position conflict through the Logit model given in Eq. (8). If not, pedestrians could continue to move.

Step 5: Repeat steps 3-4 for the consecutive 10 time steps.

Step 6: Repeat steps 2-5 until all pedestrians leave the room.

III. SIMULATIONS

A. MODEL VALIDATION

In this section, k_S and k_D in Eq. (1), α and β in dynamic field need to be calibrated, which could determine the validity of the model. Trial-and-error method [51] is used to calibrate the above parameters according to simulation results of the model. All parameters are input into the model for operation. The movement dynamics of pedestrians during the simulation is observed, and the evacuation time and the ratio of pedestrians leaving from each exit are defined as the basis for parameter adjustment. The parameters with the smallest error are adopted. Finally, $\alpha = 0.2$, $\beta = 0.05$, $k_S = 1.8$ and $k_D = 0.1$.

The experiment B in [52] is also conducted with the developed model in this paper. Note that during the model validation, the simulation scenario in this paper keeps the same with that in [52]. FIGURE 6 shows the comparison results of the numbers of pedestrians leaving from each exit. We can find that the difference between the simulation result based on the model in this paper and the real data is within the acceptable range, which demonstrates the validation of the proposed model. In addition, the simulation results obtained by our proposed model are closer to the real data compared with the results based on the model in [52]. This further indicates the advantages of the method in this paper.

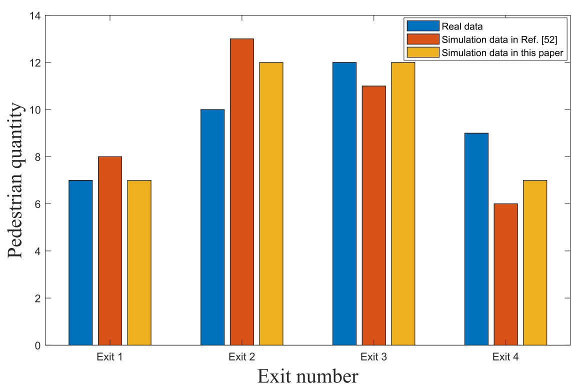


FIGURE 6. Comparison results of the number of pedestrians leaving from each exit.

B. EVACUATION DYNAMICS

The simulation scenario is shown in FIGURE 7. Three exits locate in the middle of the lower wall (exit 1), the upper wall (exit 2), and the right wall (exit 3), respectively. Their widths are 1 m, 1.5 m and 2 m. The size of room is 50 m × 50 m. The room is divided into 100 × 100 cells, which means each cell is 0.5 m × 0.5 m. The cell has two states that are empty or occupied by a pedestrian. FIGURE 8 further shows the static field of the room according to the definition of model. It could be found that the closer the exit is, the larger the static field value is. Note that each result in this paper comes from 20 repeated simulation experiments and the median value is taken as the final data. In fact, the robustness of the results could be well verified by 5 repeated experiments [53].

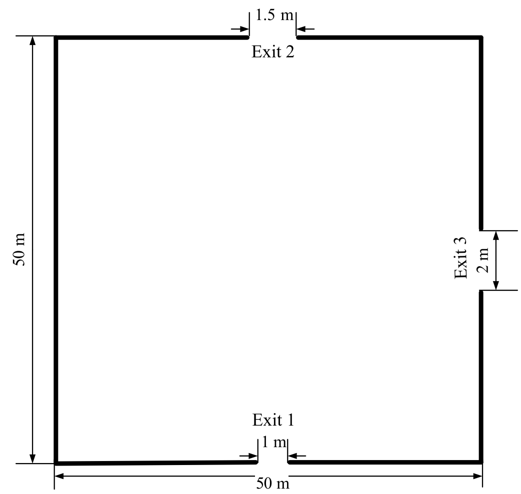


FIGURE 7. The diagram of the room.

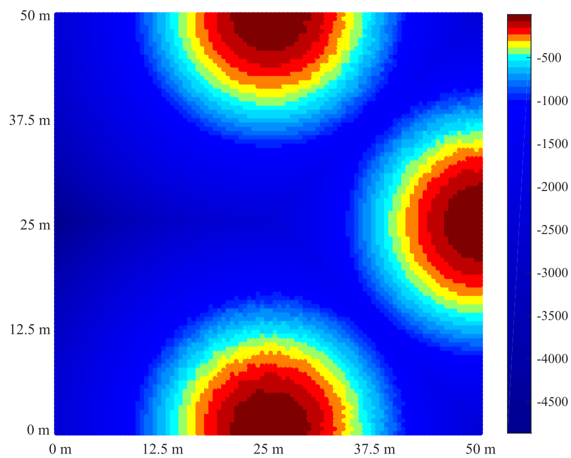
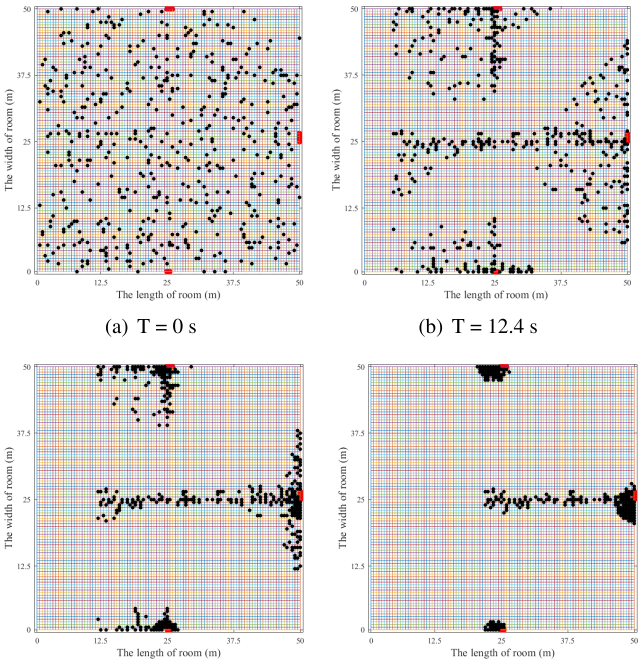


FIGURE 8. Static field of the room.

A complete pedestrian evacuation process is recorded, and some snapshots are given in FIGURE 9. FIGURE 9(a) shows the initial state of the evacuation process. 500 pedestrians randomly distribute in the room. FIGURE 9(b) shows that pedestrians move to their target exits which are determined by the fuzzy logic method and herding behaviors together. After a period of time, most pedestrians arrive at the exits or even leave the exits as shown in FIGURE 9(c). Limited by the width of the exit, the number of pedestrians leaving the room is smaller than the number of pedestrians arriving at the exit. Thus, the density of pedestrians near the exit increases which results in congestion, and the phenomenon of "arching" occurs which is very obvious in FIGURE 9(d).

Heating value of each cell is given in FIGURE 10. Here, the heating value of each cell is defined as the ratio of the number of pedestrians passing by each cell and the total evacuation time in a complete evacuation process. Different colors are used to represent the heating values in FIGURE 10, and the pedestrian trajectories could be observed.



(a) T = 0 s (b) T = 12.4 s

(c) T = 20.8 s (d) T = 42.8 s

FIGURE 9. Snapshots of pedestrian evacuation at different time instants.

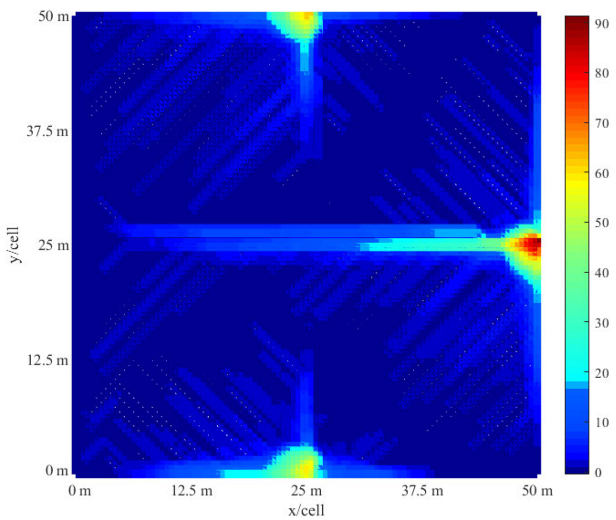


FIGURE 10. Heating value of each cell after an evacuation.

FIGURE 11 shows the change in pedestrian evacuation efficiency indicated by evacuation time with the number of pedestrians and their initial positions in the simulation scenario with the exit layout given in FIGURE 7. Note that pedestrians are initially distributed in the upper left, upper right, lower left, lower right, and middle of the room, respectively. From FIGURE 11, we can find that the pedestrian evacuation time has a positive correlation with the number of people to be evacuated, which is consistent with our empirical knowledge. Besides, the initial position of the pedestrian will also have a certain influence on the overall evacuation efficiency, which results from the effect of locations of exits.

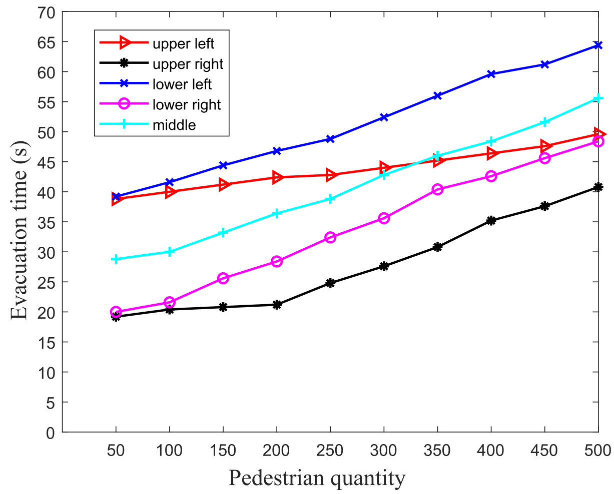


FIGURE 11. The relationship between evacuation time and the pedestrian quantity in the room at the initial time under different pedestrian initial positions.

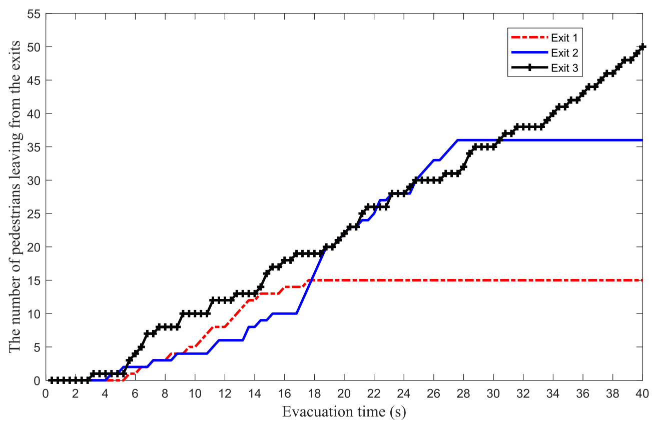


FIGURE 12. The relationship between the numbers of pedestrians leaving from different exits and evacuation time.

FIGURE 12 shows the variation of the number of pedestrians leaving from different exits with time, and FIGURE 13 further gives the specific ratios of pedestrians leaving from different exits. Note that 100 pedestrians randomly distributed in the room at the initial time. We could find that pedestrians who are near the exit could leave the room after moving for a small period of time. The ratios of pedestrians evacuating from different exits are approximately equal to the ratios of the widths of exits.

C. THE EFFECT OF EXIT ATTRIBUTES ON EVACUATION

FIGURE 14 shows how pedestrian evacuation efficiency is affected by exit layout. Note that the length and width of the room who has two exits are 50 m during the simulation, respectively. The widths of exits are both 1 m. E_1 represents the two exits are located at (25 m, 0 m) and (25 m, 50 m), E_2 represents the two exits are located at (25 m, 0 m) and (50 m, 25 m), and E_3 represents the two exits are located at (10 m, 0 m) and (30 m, 0 m). FIGURE 14 reflects that

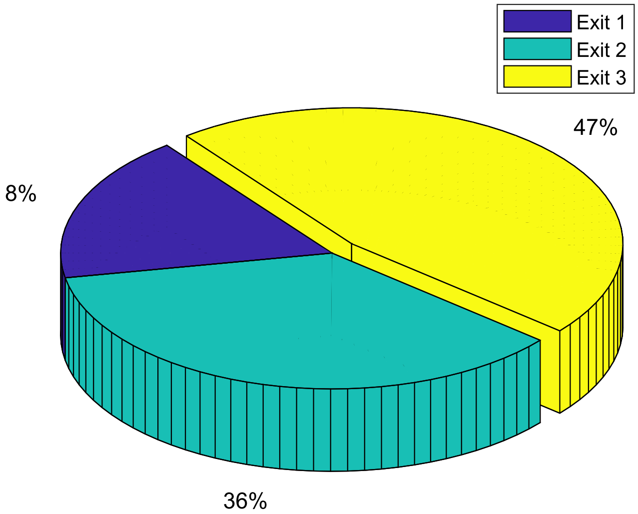


FIGURE 13. The proportions of pedestrians leaving the room through different exits.

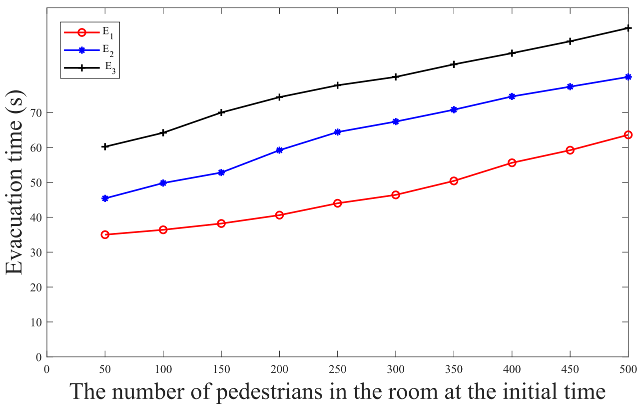


FIGURE 14. The relationship between evacuation time and the exit layout.

evacuation time under the situation with exits E_1 which are located on opposite sides of the room is the shortest compared with the other two situations. This is because the layout of the exits E_1 is helpful to reduce the distance between some pedestrians and the exit. Meanwhile, when the two exits are on the same side, it is the most unfavorable situation for evacuation.

Moreover, we increase the number of exits to study whether the evacuation efficiency can be further improved, and if so, to what extent? FIGURE 15 shows the number of passengers remaining in the room as the evacuation time changes under different numbers of exits in a simulation. Note that the initial number of pedestrians in the room is 300. For the scenario with two exits, the positions of the two exits correspond to the positions of exits 1 and 2 in FIGURE 7. For the scenario with three exits, the positions of the three exits keep the same with those in FIGURE 7. The widths of all exits are 1.5 m. FIGURE 15 reflects that the third increased exit attracts some pedestrians which could ease congestion at the other two exits, thus more pedestrians could

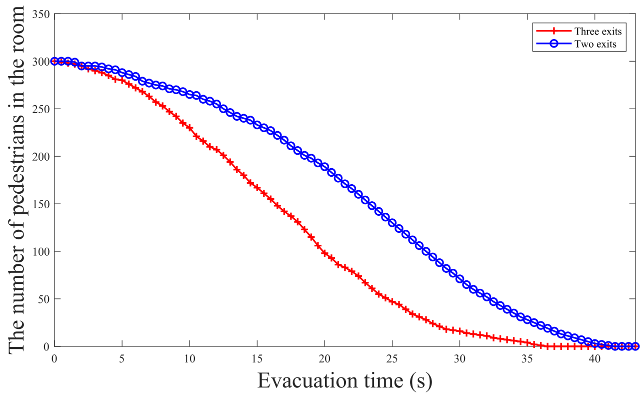


FIGURE 15. The relationship between evacuation time and the exit quantity.

leave the room within a certain time under the situation with three exits. TABLE 2 lists the mean evacuation time and its standard deviation after 20 times simulation experiments, which further reflects that three exits can indeed improve the evacuation efficiency compared with the situation of two exits.

TABLE 2. The data analysis of different simulation experiments.

	Two exits	Three exits
Mean evacuation time (s)	36.7	32.4
Standard deviation of evacuation time	1.6808	1.1937

FIGURE 16 shows how pedestrian evacuation efficiency is affected by exit width. Note that three exits during the simulation have the same positions as the exits in FIGURE 7 except that the widths of exits are different which are given in TABLE 3. In the initial time, 300 pedestrians randomly distributed in the room. FIGURE 16 indicates that increasing the exit width within a certain range can improve the evacuation efficiency, but it has little effect on decreasing the evacuation

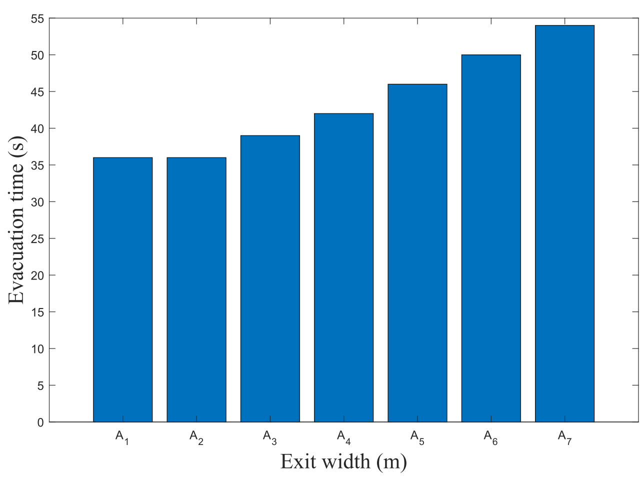


FIGURE 16. The relationship between evacuation time and the exit width.

TABLE 3. The widths of three exits in different cases A_k.

A_k	Exit 1 width (m)	Exit 2 width (m)	Exit 3 width (m)
A_1	4	4	4
A_2	3	3	3
A_3	2	2	2
A_4	2	1.5	1.5
A_5	1.5	1.5	1.5
A_6	1.5	1	1
A_7	1	1	1

time when the exit width is increased to a certain extent. For example, although the width of the exit in the case A_1 increases by 1 m compared with that in the case A_2, the overall evacuation time does not decrease significantly. This could result in the reduction of exit utilization.

D. THE EFFECT OF OBSTACLE ATTRIBUTES ON EVACUATION

Obstacles could affect the movement of pedestrian during evacuation. In this paper, obstacles are defined as all objects that may hinder pedestrian movement. According to [54], the length of the obstacle (L), the distance to the exit (G), and the offset (P) are three important attributes of the obstacle as shown in FIGURE 17. Among which, P is the distance between the center point of the obstacle and the exit on the same horizontal line. SD is the safe distance between pedestrians and the obstacle. $SD = 0.5$ m in this paper.

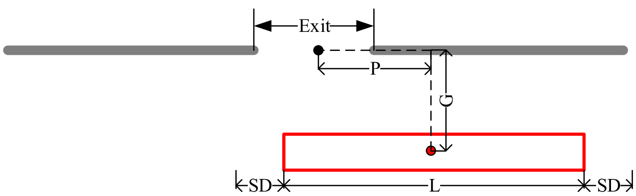


FIGURE 17. The attributes of obstacle.

During the evacuation process, we specially set that when the obstacle appears in the pedestrian's vision field, the pedestrian begins to detour to the end of the obstacle that is closer to the pedestrian. After avoiding the obstacle, the pedestrian continues to move toward the exit. In order to test the feasibility of the obstacle avoidance rule, the comparison results of the simulation data of this paper and [54] are studied as FIGURE 18 shows. We can find that the simulation results are basically the same and there is no big difference, thus the rationality of the rule is verified. It is worth note that the simulation scenario keeps the same during the comparison.

In the simulation scenario of FIGURE 7, we specially add an obstacle with the same attributes near each exit. The effects of parameters L, G, P of obstacles on evacuation efficiency are studied, and the simulation results are shown in FIGURES 19-21.

FIGURE 19 shows the effect of parameter L on evacuation efficiency under different values of G. When $L = 0$ representing no obstacle scene, the evacuation time is around 40 s.

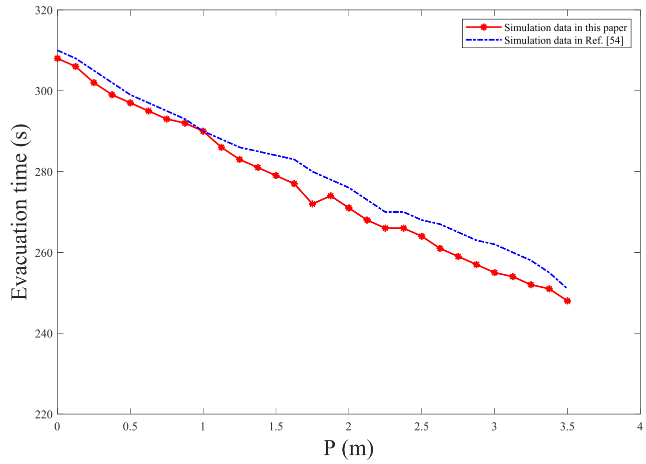


FIGURE 18. The comparison results of the simulation data in this paper and in Ref. [53].

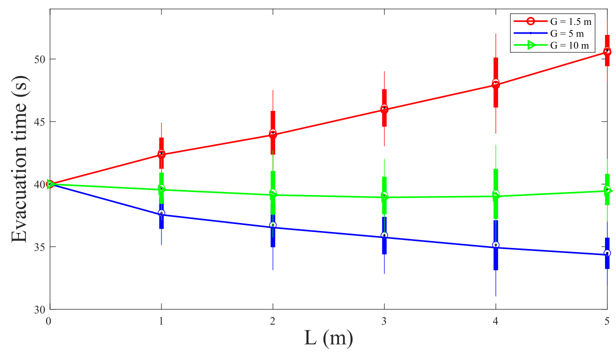


FIGURE 19. The relationship between evacuation time and L under different G. $P = 0.5$ m. There are 200 pedestrians in the room at the initial time.

With the increase of L, the trend of evacuation time is obviously different for different G. When $G = 1.5$ m, the evacuation time increases with the increase of L. The larger the L is, the greater the influence on the evacuation time is. When $G = 5$ m, the evacuation time decreases with the increase of L. Besides, the decrease degree of evacuation time begins to slow down with the increase of L. When $G = 10$ m, the change of L has little effect on evacuation time. Therefore, the value of G has a significant impact on the effect of evacuation.

FIGURE 20 further shows the influence of increasing G on evacuation time when L and P are fixed. From this figure, it can be observed that with the increase of G, the evacuation time first decreases and then increases to the evacuation time which is close to the no obstacle scene. The decrease of evacuation time is due to the expansion of the area between the obstacle and the exit, thus alleviating the excessive congestion near the exit. However, if G continues to increase, the distance between the obstacle and the exit is too large, which has little effect on the diversion of pedestrians near the exit. At this time, the obstacle could cause pedestrians to spend more time

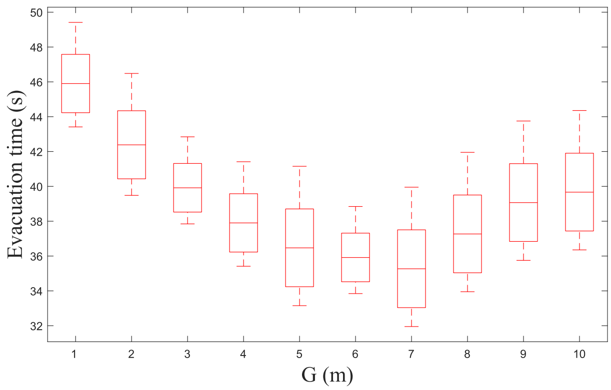


FIGURE 20. The relationship between evacuation time and G. $P = 0.5$ m and $L = 2$ m. There are 200 pedestrians in the room at the initial time.

to bypass. So there is an optimal G during the process of setting up obstacles.

FIGURE 21 shows the change of evacuation time with the increase of P in the case of different G. When $G = 1.5$ m, the obstacles gradually deviate from the exit with the increase of P, which can avoid further aggravation of pedestrian congestion near the exit and save the detour time. Thus, the overall evacuation time could be reduced. When $G = 5$ m, the segmentation effect of obstacles on the pedestrian flow around the exits weakens with the increase of P. The pedestrian density near the exit increases, thus the evacuation efficiency decreases. When $G = 10$m, the value of P has little effect on evacuation time.

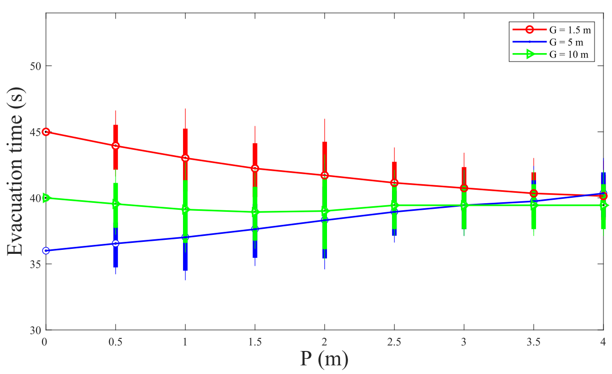


FIGURE 21. The relationship between evacuation time and P. Meanwhile, $G = 1.5$ m and $L = 3$ m. There are 200 pedestrians in the room.

In sum, there are advantages and disadvantages in the effect of obstacles on evacuation. On the one hand, obstacles may reduce space utilization and increase the detour time of pedestrians. On the other hand, it may alleviate the crowd around the exit. Therefore, parameters L, G, P of obstacles need to be studied in advance based on simulation results in order to improve the evacuation efficiency.

IV. CONCLUSION

The microscopic cellular automata model is used to simulate pedestrian movement in this paper, in which the logit method is adopted to solve the position conflicts of pedestrians. The fuzzy logic method which is good at describing the fuzziness in human decision-making is combined to guide the exit selection of pedestrians. Moreover, the herding behavior is also considered during the exit selection process. The rationality of the model is verified by comparing the simulation data with the real data. Pedestrian evacuation dynamics is further studied based on the proposed model, and the influences of exit attributes and obstacle attributes on the evacuation efficiency are investigated on the basis of simulation results. The results indicate that the initial positions and the number of pedestrians in the room do have a certain impact on the evacuation time, and widening the exit width within a certain range can speed up evacuation, which are consistent with our life experience. In the case of a room with only two exits, the exits should be set face to face. The simulation results of obstacle attributes show that the size and location of obstacles are very important for evacuation. It is necessary to design the obstacles reasonably according to the size of the room and the attribute of exits to avoid reaction. The model developed in this paper could be used to provide some specific suggestions for the construction of large public facilities.

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