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# An extended cellular automata model with modified floor field for evacuation*

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The floor field model has been widely used in evacuation simulation research based on cellular automata model. However, conventional methods of setting floor field will lead to highly insufficient utilization of the exit area when people gather on one side of the exit. In this study, an extended cellular automata model with modified floor field is proposed to solve this problem. Additionally, a congestion judgment mechanism is integrated in our model, whereby people can synthetically judge the degree of congestion and distance in front of them to determine whether they need to change another exit to evacuate or not. We contrasted the simulation results of the conventional floor field model, the extended model proposed in this paper, and Pathfinder software in a same scenario. It is demonstrated that this extended model can ameliorate the problem of insufficient utilization of the exit area and the trajectory of pedestrian movement and the crowd shape of pedestrians in front of exit in this new model are more realistic than those of the other two models. The findings have implications for modeling pedestrian evacuation.

**Keywords:** evacuation simulation, cellular automata model, floor field model, congestion

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## 1. Introduction

In recent years, urban construction has shown the trend of three-dimensional and multi-functional developments, which makes the gathering of a large number of people a normal occurrence. In the event of terrorist attacks, earthquakes, fires, and other emergencies, it is easy to cause panic among crowds, which can lead to serious casualties. In these cases, the immediate and safe evacuation of people is considered as an important factor in reducing casualties. With the rapid development of computer science, researchers have proposed and implemented many discrete or continuous evacuation models for simulating evacuations. In general, the social force model,[1,2] gas dynamic model, and fluid dynamic model[3–5] are the representative continuous models. The cellular automata (CA) model[6–8] and lattice gas model[9,10] are the representative discrete models.

CA model can reproduce the self-organizing phenomenon of crowd and has obvious advantages in describing the influence of environmental information on the movement of people. That is why many researchers choose to use CA model for evacuation simulation studies. In the process of building evacuation simulation research based on CA model, Burstedde *et al.*[11] introduced the concept of floor field into this model, and many studies were conducted on this basis. Kirchner, Schadschneider, and Nishinari, *et al.*[12,13] proposed a CA model for friction. When multiple people try to enter the same cell, a conflict occurs. At this time, the movement of other people is restricted according to a certain probability, and only one person is allowed to move to that position. Based on the model for friction, Song and Yu *et al.*[14,15] proposed an improved CAFE (cellular automata with forces essentials) model to transform the various interaction forces in the social force model into three forces: repulsion, friction, and attraction. All of the above studies lay the foundation for the research of CA model for evacuation simulation, but they did not study the influence of exits on evacuation process, which was noticed in later studies. Based on CA model with floor field, Nishinari and Kirchner *et al.*[16] proposed a method for calculating a static floor field under any room geometry. It is also mentioned that if the width of exit continues to increase, more careful handling is required when calculating the static floor field near the exit. Based on the former research, Varas and Cornejo *et al.*[17] proposed a calculation method for the floor field in the presence of obstacles in the room, and discussed the effects of the width and position of exit on the evacuation time. During the research, it was found that the width and position of exit not only affected the efficiency of evacuation, but also affected the trajectory of pedestrian movement and the crowd shape of pedestrian in front of exit. Huang and Guo[18] proposed a new static floor field calculation method using weighted sums of two neighboring models, which achieved a relatively optimal crowd gathering shape in front of exit. However, in their model, pedestrians will never change their choices even though the current situation changes. In the model established by Alizadeh,[19] pedestrians will consider the degree of con-

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gestion of different exits and distance to different exits, and then choose the exit which allow people to escape in a shorter time. Kinateder and Comunale *et al.*[20] studied how pedestrians choose exits in emergencies. Their results show that exit familiarity and neighbor behavior both influence the choice of exit. During the years of research, an increasing number of details affecting evacuation have been considered by researchers, such as the impact of escalators,[21] crutches or wheelchairs,[22] crawling behavior in fire,[23] evacuees' walk preferences on the stairs,[24] and action of guard in artificial attack.[25]

Although these details can make the model more suitable for certain specific scenes and crowds, the previous studies have not conducted a more in-depth study on the illogical movement of people in exit area. This illogical movement will lead to insufficient utilization of some exit areas, thereby increasing the evacuation time and reducing the accuracy of the simulation results. In the conventional CA model using a floor field, the exit is divided into one or more cells, which have different attractions for pedestrians. Fu and Yang *et al.*[26] considered that the geometric center of an exit is different from its attractive center. They introduced two new variables: the position deviation between the exit geometric center and the exit attraction center, and the individual tendency intensity to the exit attraction center. Thus, the uneven attraction of exit to pedestrians is realized. Their experimental result shows that when the exit is narrow, the friction between people has more influence on the evacuation time than the uneven attraction of exit to pedestrians; however, as the width of the exit increases, the influence of the uneven attraction of the exit on the evacuation time will dominate. Wei and Song *et al.*[27] also found that the value of the static floor field has a greater impact on the evacuation trajectory, and when the exit is dispersed into more than one cell owing to its large size, insufficient utilization may occur in some exit areas. They set the virtual point at a certain distance from the exit center cell outside the room and calculated the static floor field based on the virtual point. Experiments have shown that this does help to obtain a more reasonable pedestrian trajectory near the exit area. However, they only considered the single exit scenario. When there are multiple exits, people will face the problem of exit choice. When all pedestrians are on one side of an exit, the problem of illogical movement of people will be more obvious.

In order to make the simulation results of evacuation model more accurate, these problems must be solved. In this study, we propose an extended CA model with modified floor field (MFF) to ameliorate insufficient utilization of the exit area when people gather on one side of the exit. Moreover, we introduce a pedestrian judgment mechanism: when many pedestrians are blocked at a certain exit, the mechanism makes pedestrians to comprehensively consider factors such as the degree of congestion and distance in front to judge whether to replace the exit to evacuate. The rest of this paper is organized as follows. The model's details are introduced in Section 2. In Section 3, the contrast of two evacuation models and Pathfinder software, and the effects of several key parameters on pedestrian evacuation simulation are discussed. In Section 4, some conclusions are drawn from the present study.

## 2. Model description

This section described the CA model with MFF. Contrasted with other evacuation simulation methods, the calculation of this model is simpler. Initially, the room is divided into a finite number of square cells, and the pedestrian movement uses the von Neumann neighborhood (Fig. 1). The direction selection formula for each movement is as follows:

$$P_{i,j}^{m} = N\left(1-\omega_{i,j}\right)\left(1-\xi_{i,j}\right)\exp\left(k_S S_{i,j}^{m}\right)\exp\left(k_D D_{i,j}\right) \times \exp\left(k_R R_{i,j}^{t} + k_C L^{m}\left(T - C_{i,j}^{m}\right)/T\right), \quad (1)$$

where $P_{i,j}^{m}$ indicates the probability that the next time step selects to move to cell $(i,j)$ when the person intends to leave from exit $m$. $N$ is a normalization coefficient to ensure that $\sum_{(i,j)} P_{i,j}^{m} = 1$. $\omega_{i,j} = 1$ when cell $(i,j)$ is occupied by other people, and $\xi_{i,j} = 1$ when cell $(i,j)$ is occupied by obstacles or walls. $k_S$, $k_D$, and $k_R$ are respectively the weights of static floor field $S_{i,j}^{m}$, dynamic floor field $D_{i,j}$, and modified floor field $R_{i,j}^{t}$ with respect to exit $m$. $k_C$ is the congestion degree coefficient, $T$ is the total number of people in the room, $L^{m}$ is the width of exit $m$, and $C_{i,j}^{m}$ is the number of people between cell $(i,j)$ and exit $m$.

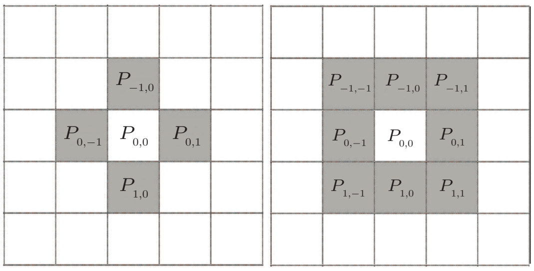


**Fig. 1.** Schematic diagram of the von Neumann neighborhood (left) and Moore neighborhood (right). The gray cells indicate the corresponding neighbors of the central cell.

In the next four subsections, the floor field, the MFF (modified floor field), the calculation of congestion degree, the random stop mechanism and the model updating rules will be introduced in detail.

### 2.1. Floor field assignment

This model is a modified version of the floor field model, which of course includes the static and dynamic floor fields. The calculation of the static floor field draws on the research by Huang and Guo.[18] When assigning a static floor field value to each cell, firstly, the minimum number $d_{VN}^{m}$ of cells required to move to the corresponding exit $m$ is calculated when the pedestrian at position $(i, j)$ is allowed to move only horizontally or vertically (von Neumann neighborhood). Then, the minimum number $d_M^m$ of cells required to move to the corresponding exit $m$ when the pedestrian at position $(i, j)$ is allowed to move in all eight directions (Moore neighborhood) is calculated. Finally, the distance metric $d_{i,j}^m$ of position $(i, j)$ to exit $m$ is obtained according to

$$d_{i,j}^m = \varepsilon d_{VN}^m + (1-\varepsilon)\, d_M^m, \tag{2}$$

where $\varepsilon \in [0.4, 0.6]$ according to the previous research.[18] After calculating the distance $d_{i,j}^m$ of all cells in the room to the corresponding exit $m$, the maximum value $d = \max_m \left\{\max_{(i,j)} d_{i,j}^m\right\}$ is found. Then the static floor field value corresponding to exit $m$ is calculated according to

$$S_{i,j}^m = d - d_{i,j}^m. \tag{3}$$

The bigger the value of $S_{i,j}^m$, the closer the cell $(i, j)$ is to exit $m$. At the same position $(i, j)$, there will be different $S_{i,j}^m$ values to different exits. In this case, the bigger one will be taken as the global static field $S_{i,j}$ of this cell $(i, j)$, as indicated in

$$S_{i,j} = \max_m S_{i,j}^m. \tag{4}$$

For cells at the exit, a maximum value can be given directly, for example $S_{\text{exit}} = 100$.

The dynamic floor field is a virtual trace left by pedestrians. It is usually employed to express people's conformity behavior, and incorporates the characteristics of diffusion and decay. Initially, all cells' $D_{i,j} = 0$ when a person moves from position $(i, j)$ to his/her neighborhood, $D_{i,j} = D_{i,j} + 1$. Therefore, the dynamic floor field changes with time. We determine the diffusion and decay of the dynamic floor field according to two probabilities $\alpha \in (0,1)$ and $\delta \in (0,1)$. In this study, diffusion means that the dynamic floor field value $D_{i,j}$ originally at cell $(i, j)$ is transferred to its arbitrary neighborhood cell $(i_0, j_0)$ by probability $\alpha$. After transferring, the neighborhood cell $D_{i_0,j_0} = D_{i,j}$ and its original location $D_{i,j} = 0$. Decay means that the dynamic floor field value $D_{i,j}$ at cell $(i, j)$ decays by probability $\delta$ to half of its original value, *i.e.*, $D_{i,j} = D_{i,j}/2$.

## 2.2. Modified floor field

In this paper, the concept of modified floor field (MFF) is proposed to change pedestrians' movement trajectory through real-time modification of floor field, so as to improve the crowd shape of pedestrians in front of exit, and ameliorate insufficient utilization of the exit area when people gather on one side of the exit.

The MFF is essentially the same as the static and dynamic floor fields. It assigns a value to a cell $(i, j)$ to control the choice of the moving direction of a pedestrian. Insufficient utilization of the exit area is mainly caused by the static floor field. The static floor field of the exit area is always diffused equivalently along the exit center to both sides. The value $S$ of the cells in the symmetrical positions of the left and right sides of the exit center is equal, which will lead to the problem that pedestrian cannot move to another side of the exit center according to Eq. (1) when people gather on one side of the exit. Therefore, we propose the MFF to solve this problem. Before calculating the MFF, we have to determine the size of the exit area $Z$ that needs to be modified, according to the total number $T$ of people that needs to be evacuated. The exit area $Z$ that needs to be modified is a rectangular area and is divided into two symmetrical and equal squares along the exit centerline. The side length of the square is as follows:

$$\text{length} = \left\lceil \sqrt{(T/2)} \right\rceil. \tag{5}$$

One of these two square areas is closer to the crowd, whereas the other is far away from the crowd. After starting the simulation, at the beginning of each time step $t$, the MFF of all cells is initialized to $R_{i,j}^t = 0$. By contrasting the difference of the number of people in the two parts of $Z$ along the exit center line, we can calculate the value $R_{i,j}^t$ of the cells on the side of $Z$ away from the crowd in this time step.

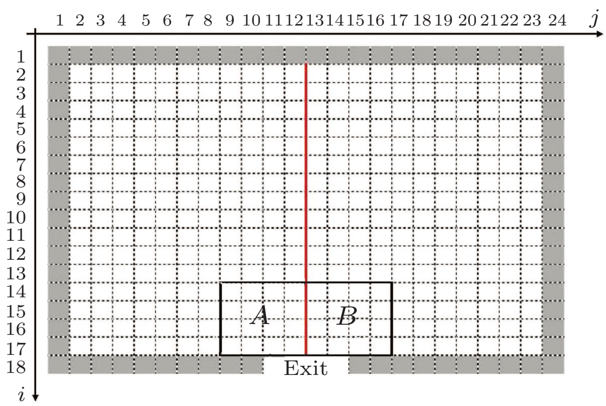


**Fig. 2.** Schematic diagram of the modified floor field. The gray cells represent the cells occupied by walls or obstacles, the red line represents the exit centerline, and the black frame area represents the hypothetical exit area $Z$. The exit area $Z$ is divided into two equal areas $A$ and $B$ by the exit centerline.

For example, suppose a scenario that is shown in Fig. 2. The location of each cell in this scenario is determined by the coordinate axis value $(i, j)$, and the origin of the coordinate axis is in the upper left corner. We assume that people gather on the right side of the exit centerline in this scenario, that is, they are closer to area $B$. At the beginning of time step $t$, first, the MFF of all cells are initialized as $R_{i,j}^t = 0$. Next, the number of people $Z_A$ and $Z_B$ respectively located in areas $A$ and $B$ at this time are counted, and the difference in the number of people is calculated by $Z_D = Z_B - Z_A$; then $R_{i,12}^t = \beta \cdot Z_D$, $(i = 14, 15, 16, 17)$ in area $A$. The farther away from the red line, the bigger the value of $\beta$. The initial value of $\beta$ is 0.01 in this study, and the increment is 0.01, as follows:

$$R^t_{i,11} = (\beta + 0.01) Z_D, \quad (i = 14, 15, 16, 17), \tag{6}$$

$$R^t_{i,10} = (\beta + 0.02) Z_D, \quad (i = 14, 15, 16, 17), \tag{7}$$

$$R^t_{i,9} = (\beta + 0.03) Z_D, \quad (i = 14, 15, 16, 17). \tag{8}$$

The computed $R^t_{i,j}$ is used for the calculation of $P^m_{i,j}$ in this time step, and after entering the next time step $t+1$, all $R^t_{i,j}$ values are initialized to 0 again, and the above operation is repeated.

### 2.3. Judgment of congestion degree

We draw on the model by Alizadeh.[19] When people choose the direction of movement at each time step, they will synthetically consider the width and congestion of different exits. This allows people to change to another exit for evacuation actively when a certain exit has a slow outflow, so that the total evacuation time will also be reduced. For example, for a pedestrian who was moving toward exit A, he found that the congestion at exit A is much greater than that at exit B, and the width of exit B is larger. A wider exit often means a faster evacuation speed. At this time, even if exit B is farther away, he may give up exit A and move towards exit B.

In Eq. (1), $k_C L^m \left(T - C^m_{i,j}\right)/T$ is the part used to judge the degree of congestion at the front exit. The distance between cell $(i, j)$ and exit $m$ can be expressed by $S^m_{i,j}$, and the value of $C^m_{i,j}$ is equal to the number of people in all cells with their static floor field value less than $S^m_{i,j}$.

It can be observed from the calculation formula of the congestion degree that people will tend to choose exits with larger widths and fewer users, which is also reflected in the model simulation experiment.

### 2.4. Random stop mechanism

Based on the research by Kirchner, Nishinari *et al.*,[13] we use a probability $\mu \in (0, 1)$ to allow people to abandon the movement of this time step and stay in place, by simply simulating various accidents that can lead to stop the movement. This feature makes the model non-deterministic. In this paper, the probability $\mu$ is not a constant value; it will change according to the number $N$ of people in the Moore neighborhood near the person. At the beginning $\mu = 0.05$, as follows:

$$\mu = 0.05 + N \cdot 0.0125. \tag{9}$$

This probability will be used when updating the model, see Subsection 2.5.

### 2.5. Update rules

The pedestrian movement in our model uses the Von Neumann neighborhood mode, where each pedestrian can only move to one of his von Neumann neighborhoods or remain in place at each time step. Before pedestrians start to move, we set the initial position of the pedestrians, obstacles, and exits, and then determine the static floor field value $S$ and the size of the exit area $Z$ according to Subsections 2.1 and 2.2. Initially, $D_{i,j} = 0$, $t = 0$. Here we assumed that the evacuation speed is $v = 1$ m/s, because each cell is a square with a side length of $l = 0.5$ m, and person moves at most one cell in each time step, so the evacuation time here is $t \cdot (l/v)$ .

In a simulation, pedestrians moving are synchronously updated. For all the pedestrians, the evacuation simulation process at each time step is described below.

**Step 1** Start the movement of time step $t$.

**Step 2** At the beginning of each time step, let $R_{i,j} = 0$, and calculate $R_{i,j}$ of this time step according to Eqs. (6)–(8).

**Step 3** Obtain the random stop probability $\mu$ of this pedestrian according to Eq. (9), and judge whether this pedestrian moves or not. If he moves, go to Step 4; otherwise, end the movement of this time step and wait for the movement of time step $t+1$.

**Step 4** Calculate the degree of congestion of this pedestrian corresponding to different exits according to Subsection 2.3.

**Step 5** Calculate the probability value of each moving direction according to Eq. (1) and select the direction with the largest probability value to move. If more than one pedestrian tries to enter the same cell, randomly select one of them as the collision winner to enter the cell,[15] and the other stays at the original cell and ends the movement of this time step, waiting for the movement of the next time step.

**Step 6** Update $D_{i,j}$ according to the movement of pedestrians and calculate the diffusion and decay of the dynamic floor field according to Subsection 2.1.

**Step 7** If all the pedestrians in the room have evacuated through exits, stop the simulation and the evacuation time is $t \cdot (l/v)$; otherwise, $t = t+1$ and return to Step 1, all pedestrians begin the movement of the new time step.

## 3. Results and discussion

In this section, we analyze the influence of different parameters of the model on the experimental results, and contrasted the simulation results of the conventional floor field model, the new model proposed in this paper, and Pathfinder software in a same scenario.

To obtain a more accurate model contrast effect, a simple rectangular room is built as the experimental scenario. The size of the room is 17 m $\times$ 22 m, and the room is discretized into 34 $\times$ 44 cells. As there is only a room without internal compartments in this scenario, the thickness of the wall will not affect the experimental results. For the convenience of expressing the location of the wall and exit, we assume that the thickness of the wall and the exit is one cell (0.5 m). In this case, the experimental scenario consists of 36 $\times$ 46 cells. In the initial scenario, two exits with a width of 2 m are placed in the room, as shown in Fig. 3.

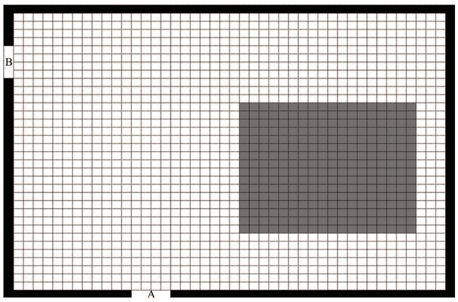


**Fig. 3.** Schematic diagram of the experimental scenario. The black cells are occupied by walls or obstacles, gray cells are occupied by pedestrians, and A and B are two different exits.

To demonstrate more clearly the inadequacy of the conventional CA model in the simulation where people gather on one side of an exit, this study places the initial positions of pedestrians together as shown in Fig. 3, and the total number of people is 288. We set up such a large number of people in the hope that we can more clearly observe the congestion in the experiment.

The initial parameters are as follows: static floor field weight $K_{\mathrm{s}} = 0.1$, dynamic floor field weight $K_{\mathrm{D}} = 0.1$, MFF weight $K_{\mathrm{R}} = 1$, congestion degree factor $K_{\mathrm{C}} = 10$, weight $\varepsilon = 0.5$, for calculating floor field, random stop probability $\mu = 0.05$, diffusion probability $\alpha = 0.5$, and decay probability $\delta = 0.5$ of dynamic floor field. Some parameters may be changed later.

In the parameter analysis, the model proposed in this study is extended based on the conventional CA model. Many of the parameters, such as static floor field, dynamic floor field, or exit width, have been discussed many times; thus, they will not be repeated here. We mainly discuss the effect of congestion degree coefficient $K_{\mathrm{C}}$ and MFF weight $K_{\mathrm{R}}$ on the evacuation time.

### 3.1. Analysis of congestion degree coefficient

In this section, we discuss the impact of congestion degree coefficient $K_{\mathrm{C}}$ on the evacuation simulation results of the extended CA model with MFF. The parameters and experiment scenario (see Fig. 3) are the same as before.

The effect of different congestion degree coefficients $K_{\mathrm{C}}$ on evacuation time is shown in Fig. 4. The total evacuation time is determined by the time when the last person completed the evacuation. This means that the bigger value of last_A and last_B is the evacuation time of the entire scenario. The effect of $K_{\mathrm{C}}$ on the number of people using different exits is shown in Fig. 5. As $K_{\mathrm{C}}$ increases last_A decreases sharply and then tends to be stable and last_B increases sharply and then tends to be stable in Fig. 4. This is because as the influence of the congestion judgement mechanism on pedestrian movement increases, more and more pedestrians whom were originally blocked at exit A (the exit which is closer but has a greater number of users) turn to exit B, resulting in fewer people using exit A and more people using exit B (see Fig. 5). With the increase in $K_{\mathrm{C}}$, the difference in the number of people using the two exits gradually decreases until it becomes stable, but this difference will always exist due to exit A is closer to the initial position of the crowd.

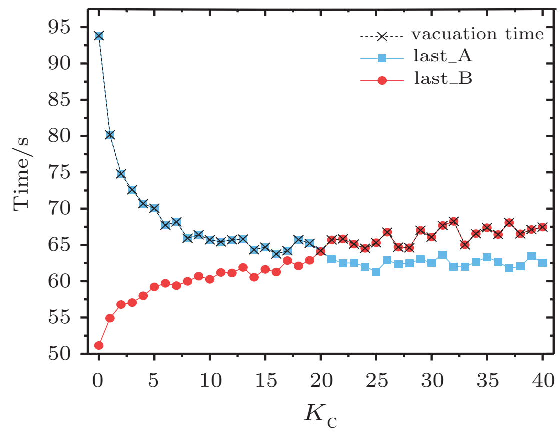


**Fig. 4.** Effect of $K_{\mathrm{C}}$ on the evacuation time of two exits. Last_A and last_B respectively indicate the time when the last person evacuated exits A and B with different $K_{\mathrm{C}}$. Evacuation time is the larger value between last_A and last_B with the same $K_{\mathrm{C}}$.

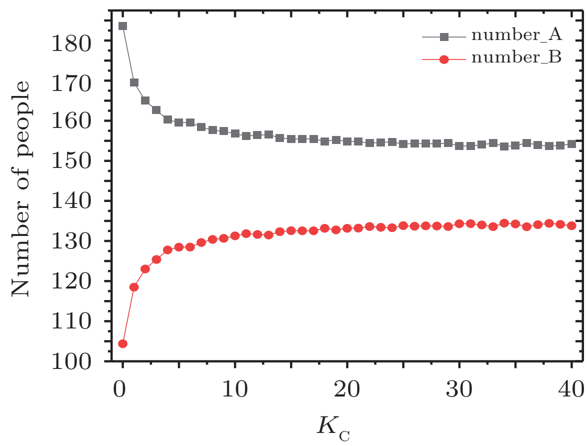


**Fig. 5.** Effect of $K_{\mathrm{C}}$ on the number of people evacuated through two exits. Number_A and number_B respectively represent the number of people using exit A and exit B to evacuate.

The effect of different $K_{\mathrm{C}}$ values on evacuation time under different numbers of people $T$ is shown in Fig 6. First, the most significant trend is of course that the fewer the number of people, the shorter the evacuation time. Second, when the number of people is large, with the increase in $K_{\mathrm{C}}$, the evacuation time first decreases sharply and then tends to stabilize. However, with the decrease in the number of people $T$, when $K_{\mathrm{C}}$ increases, the evacuation time first decreases sharply and then increases slowly. This is because the influence factor of the congestion degree is extremely large in the selection of the movement direction of the pedestrian, resulting in a meaningless behavior of replacing the exit, which wastes time on the way of replacing the exit. For example, when $K_C$ is large ($> 15$), there will be a person who is clearly close to exit A, and only a few people in front will not cause congestion. When all people can complete the evacuation in a relatively short time (in a few seconds), the person still chooses to change the target to the exit with fewer current users; therefore, there will be no significant increase in the total evacuation time. This situation is more obvious in the scenario where the total number of people to be evacuated is small, because when the number of people is small and the room is large, it takes less time for people to queue to escape through the same exit than change an exit with fewer people but longer distance to escape.

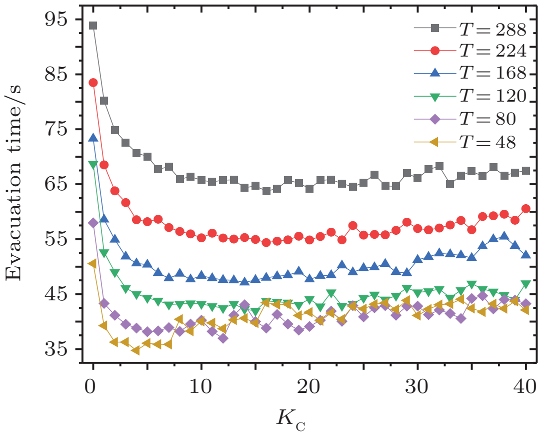


**Fig. 6.** Effect of $K_C$ on evacuation time under different numbers of people $T$.

Therefore, we consider that the optimal range of $K_C$ in the scenario set in this study is $8 \leq K_C \leq 15$; thus, the congestion degree coefficient above is set as $K_C = 10$ in our experiment.

### 3.2. Analysis of the weight of modified floor field

Here, we discuss the influence of different weights $K_R$ of MFF (modified floor field) on evacuation time in our model. The parameters and scenario (see Fig. 3) are the same as before.

Since the MFF is established based on exit A in this experiment, the change of $K_R$ has a greater effect on exit A and a relatively smaller effect on exit B. It can be observed from Fig. 7 that the evacuation time decreases first and then increases with the increase in weight $K_R$ of MFF. When $K_R$ is small ($0 \leq K_R \leq 3$), the utilization of the partial area of the exit is improved, so the evacuation efficiency of exit A is improved, which leads to the decrease of last_A. Due to the existence of congestion degree judgment mechanism, with the improvement of evacuation efficiency at exit A, the number of people who choose to replace the exit decreases, that is, the number of people who pass through exit A increases, and the number of people who pass through exit B decreases, resulting in a reduction in last_B. However, as $K_R$ continues to increase, the evacuation time starts to increase instead. As the correction of floor field by MFF continues to increase, it will cause some areas of the room to be more attractive to pedestrians than exits, thus preventing pedestrians from going to exits to complete the evacuation and increasing the evacuation time. This is also the main reason for the increase of last_A and the secondary reason for the increase of last_B. The main reason for the increase in last_B is that the congestion judgment mechanism affects the choice of evacuation exits, causing people who were originally blocked at exit A to switch to exit B, which increases the number of people using exit B, so last_B also increases. Therefore, in our experiment, the MFF weight is set as $K_R = 1$.

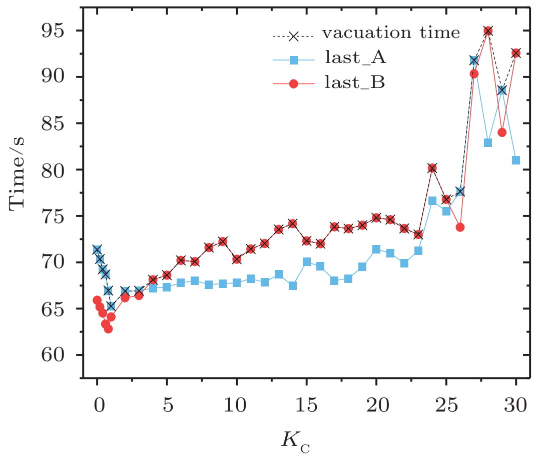


**Fig. 7.** Effect of $K_R$ on the evacuation time of two exits. Last_A and last_B respectively indicate the time when the last person evacuated exits A and B with different $K_R$. Evacuation time is the larger value between last_A and last_B with the same $K_R$.

### 3.3. Model contrast

Pathfinder is an advanced movement simulation tool combined with high-quality three-dimensional animated results. It is worth to point out that there are also many important research results,[28,29] which are obtained based on Pathfinder; therefore, we use it as part of our contrast experiment.

The parameters and scenario (see Fig. 3) are the same as before. We use the extended CA model without MFF, extended CA model with MFF, and Pathfinder software to simulate pedestrian evacuation and obtain the spatial usage intensity map of the evacuation scenario, as shown in Figs. 8–10, respectively. The intensity map represents how long a certain position in the scenario has been used throughout the evacuation process. The longer the time the position is used, the more the color tends to be dark red, and the position where the time is shorter is darker blue. Based on the intensity map, we can clearly observe the movement trajectory of the group of people.

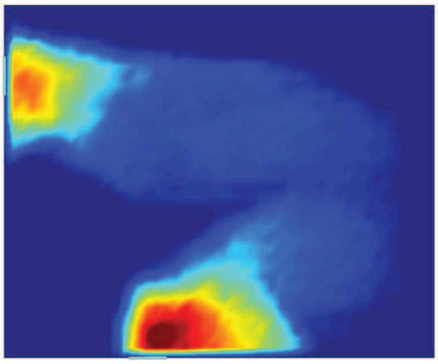

**Fig. 8.** Space usage intensity map of the model without MFF.

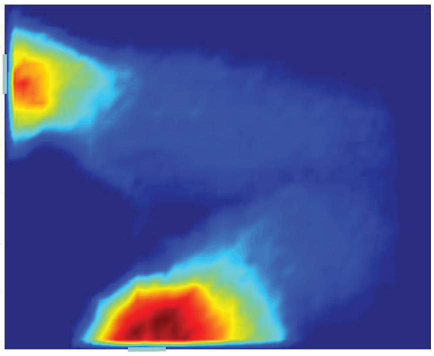

**Fig. 9.** Space usage intensity map of the model with MFF.

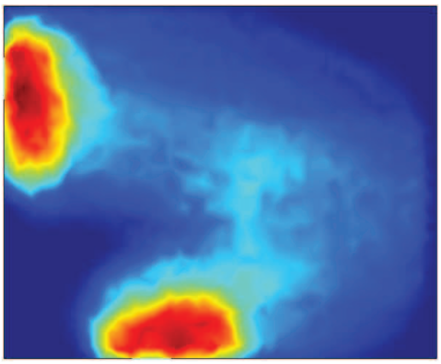

**Fig. 10.** Space usage intensity map of Pathfinder.

In the simulation results obtained from the model without MFF (see Fig. 8), there is an illogical situation in the pedestrian movement trajectory at the exit. In particular, there is almost no pedestrian movement in the left area at exit A. The ideal pedestrian trajectory should appear as a fan or elliptical shape centered on the exit. As shown in Fig. 10, in the simulation results obtained by Pathfinder, the movement trajectory of pedestrians at the exit is approximately elliptical. However, there are also some problems with this very regular shape because the initial position of the pedestrian is concentrated on the right side of the room, which will have a significant impact on the pedestrian trajectory near the exit. The space utilization rate on the side close to the crowd must be higher than that away from the crowd. This is also reflected in the dynamic display of the evacuation process of Pathfinder. Some pedestrians do not follow the "proximity principle" in their movement, and they choose to detor to the side of the exit away from the crowd. This behavior may occur during a non-hazardous drill, but in a real emergency, the pedestrian must choose to reach the exit as soon as possible to escape.

Figure 9 shows the simulation results obtained from the model with MFF. The shape of the pedestrian trajectory in this figure is intermediate between the shape in Figs. 8 and 10. The pedestrian trajectory at exit A is a typical ellipse-like shape, and an integral trajectory that is shifted to the upper right side caused by the crowds gathering on the right side of the room can be observed. Contrasting Figs. 8 and 9, it can be found that there is a behavior of some people changing exits in Fig. 9, but not in Fig. 8. This is also reflected in Fig. 11, the number of people evacuated by exit A in the model with MFF is bigger than that in the model without MFF. The reason for this phenomenon is described below.

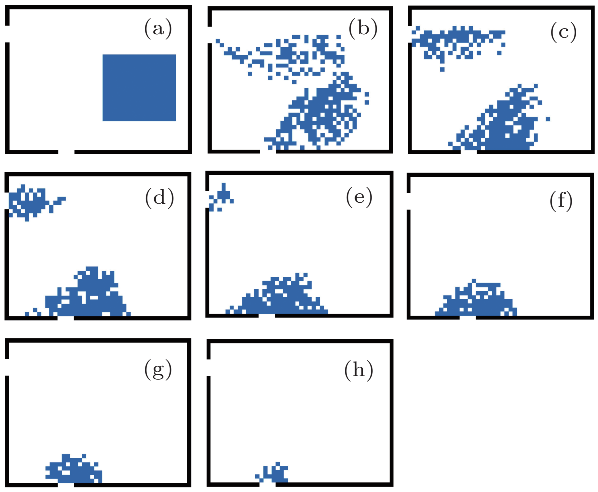


**Fig. 11.** Screenshot of the simulation process of the conventional CA model. Each gray dot in the picture represents a person. Screenshot time is after the start of simulation: panels (a), (b), (c), (d), (e), (f), (g), and (h) denote 0 s, 15 s, 30 s, 45 s, 60 s, 75 s, 90 s, and 115 s, respectively.

Here the exits A and B have the same width, so whether to replace the exit is mainly affected by the distance to the exit and the number of people at the exit. Pedestrians on the left side of exit A are closer to exit B than those on the right side of exit A. Therefore, under the same congestion situation, people on the left side of exit A are more likely to change the exit than those on the right side of exit A. In the simulation using the model without MFF, a large number of people are stacked on the right side of exit A, which is far away from exit B. Pedestrians judge that the benefit of continue to use exit A is greater even exit A has more users but is closer, so no one changes the exit. In the model with MFF, pedestrians are distributed on both sides of exit A, and the pedestrians on the left side of exit A are closer to exit B than those on the right side of exit A. Therefore, during the evacuation process, some people on the left side of exit A may judge that the benefit of using exit B is greater even exit B is far away but has less users, and thus the behavior of replacing the exit occurs.

The results of the evacuation simulation of the three models are summarized in Table 1. Because there is a random stop mechanism in the CA model, and when the probability of multiple candidate movement directions of a pedestrian is the same, one direction will be randomly selected to move, resulting in a certain difference between each experimental result of the same model. Therefore, the data used below are the average of 100 independent experiments (with two decimals), so the number of people which should have been integers has become decimals. It can be observed from Fig. 11 that the extended CA model with MFF has the shortest evacuation time, and there is not much difference in evacuation time between the other two models. In the simulation results of Pathfinder, there is not much difference in the number of people evacuated at exits A and B. However, in both two CA models, it is obvious that there are more people using exit A, because exit A is closer to the initial position of most people than exit B. At the beginning of the evacuation simulation, most of the people subconsciously want to escape to the nearer exit A. It is difficult to distribute people to different exits on such an average in Pathfinder during an emergency. Moreover, there is also a problem with the choice of exits in Pathfinder, the last person who passes through exit A is at 64 s after the beginning of evacuation, while the last person who passes through exit B is at 73.6 s after the beginning of evacuation. If we can enable more people to use exit A, then the evacuation time will be reduced, just like the simulation results of the extended CA model with MFF.

The extended CA model without MFF takes a longer time because of the lower usage rate in the exit area, which causes pedestrians to be blocked on the right side of exit A (the side close to the starting position of the crowd), while the left side of exit A (the side far from the starting position of the crowd) has almost no people moving, and the overall evacuation efficiency is low. We separately counted the number of people evacuated using the left and right sides of the center line of exit A, and calculated the difference between the two sides. The difference is 21.94 in the model without MFF, the difference is 8.86 in the model with MFF, and the difference is 3 in Pathfinder. The larger the difference, the more illogical the crowd shape of pedestrians in front of the exit, and the more obvious the problem of insufficient utilization in some areas of the exit. The experimental results show that MFF can balance the utilization of both sides of the exit and improve the evacuation efficiency.

**Table 1.** Results of the evacuation simulation of the three models.

| Model | Number of evacuated persons at different exits | | Time consumed/s |
|---|---|---|---|
| | Exit A | Exit B | |
| CA model without MFF | 164.98 | 123.02 | 74.16 |
| CA model with MFF | 158.70 | 129.30 | 66.96 |
| Pathfinder | 141 | 147 | 73.8 |

In summary, the extended CA model with MFF is more suitable for evacuation simulation in this specific situation which we used in the experiment than Pathfinder software and conventional model without MFF, whether in terms of the trajectory, total evacuation time consumed, or number of people using different exits. Furthermore, owing to the existence of a congestion judgment mechanism, when an accident occurs in an exit and the evacuation efficiency is reduced (causing a large number of people to be blocked), pedestrians will choose the appropriate exit to escape according to the real-time number of people and exit distance. For example, in the previous scenario, we artificially reduce the evacuation efficiency of exit A. The rest of the scenarios are set up in exactly the same way.

A contrast of the simulation processes between the conventional CA model and the model proposed in this study is shown in Figs. 11 and 12. It can be observed from Fig. 11 that a large number of pedestrians are crowding together at exit A (the lower exit). Even if there are no pedestrians at exit B, no one chooses to replace the exit, but blindly blocks exit A. The final evacuation time of the model is 132.5 s. As can be observed from Fig. 12, owing to the low efficiency of evacuation at exit A, a large number of pedestrians are blocked; therefore, pedestrians constantly choose to change the exit to escape. Finally, the evacuation time of the model is 108.5 s. It can be observed from the contrast that the extended CA model proposed in this study has a better performance than the conventional CA model in terms of pedestrian movement. People will judge the congestion degree of the front exit in real time. After comprehensive consideration, they judge whether to replace the exit. The pedestrian movement in our model is also closer to reality, which can get more accurate evacuation simulation results.

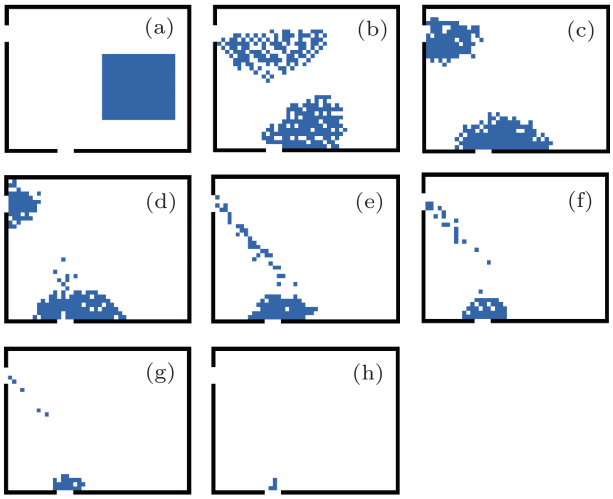


**Fig. 12.** Screenshot of the simulation process of the improved CA model with MFF. Each gray dot in the picture represents a person. Screenshot time is after the start of simulation: panels (a), (b), (c), (d), (e), (f), (g), and (h) denote 0 s, 15 s, 30 s, 45 s, 60 s, 75 s, 90 s, and 115 s, respectively.

## 4. Conclusion and prospects

In conclusion, it is important to note that the results of this study or any other related experiment may be specific to the characteristics of the test, *e.g.*, the test geometry, participant starting positions, or number of participants. Therefore, the results may not be applicable to all exit situations. Nevertheless, there is no reason to assume that the observed phenomena would only occur in this specific setting. Regardless of the geometric shape of the scenario, the static floor field is symmetrical along the exit centerline. Provided the pedestrians are not symmetrically distributed along the centerline, it will inevitably lead to pedestrians being hindered when they want to cross the centerline, resulting in low utilization of the exit. Our experiment provides a new and simple way of solving this problem and our model also integrates the exit selection mechanism to make pedestrians more intelligent. Furthermore, because of its simple rules and fast calculation speed, our CA model is easily analyzed and is very helpful to the applications. These findings have implications for modeling the pedestrian evacuation.

By studying the model parameters and contrasting different models and softwares, we could draw the following conclusions.

(i) The simulation results illustrate that the extended CA model with MFF can ameliorate the problem of insufficient utilization of the exit area.

(ii) The weight of MFF should be appropriate: an extremely small weight will make the MFF ineffective, whereas an excessively large one will lead to insufficient attraction of the exit to pedestrians and cause the evacuation time to increase.

(iii) An excessive number of pedestrians are not conducive to evacuation because it is easier to cause jam in front of exit. Therefore, a maximum capacity should be set for some public places.

Prospects for future research are put forwarded below.

(I) The shape of MFF can be more elaborate rather than a simple rectangle. Even the correction range of MFF can be updated over time.

(II) In the scenario set in this study, there are no obstacles that can block people's view. However, public places tend to have larger and more complex structures in reality. People cannot directly grasp the situation outside their sight, and it is also impossible to complete the judgment of the congestion degree mentioned in this article. Therefore, for public places with complex structures or illumination failures, a parameter should be added to help the model obtain more accurate simulation results, as in the research[30] by Leng *et al.*

(III) Establish an evacuation navigation system to display the evacuation situation of each exit and corridor in real time to solve the problem of limited vision mentioned above and help people complete the evacuation faster.

(IV) Combining the floor field model with a disaster scenario to investigate the impact of disasters on evacuation, *e.g.*, fire and smoke.[31]

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