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Simulation Model for the Decision-Making Behavior in Pedestrian Evacuation with Floor Field Cellular Automata Approach

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Abstract

In order to simulate pedestrian evacuation from a room with multiple exits, an extended floor field cellular automata (CA) model is proposed to describe the decision-making behavior of pedestrians in a realistic way. The problem of the potential distortion and reciprocating route of pedestrians is solved. Meanwhile, the visual factor and the visual field are introduced to reveal the effect of visual sense on intelligent decision-making behavior of evacuees. To make the simulation more reasonable, human psychological behaviors are considered in the model, such as panic psychology, self-protection awareness, competition awareness, etc. Moreover, the width and the layout of exits are also taken into account and the critical value is obtained by simulation. The results show that the proposed CA model is efficient and realistic in the assessment of both human evacuation and building design.

Keywords*: cellular automata; pedestrian evacuation; decision-making; exit conditions*

1. Introduction

The theory of emergency evacuation is the multi-agent systems which are composed of both the pedestrians and the environment, involving psychology, statistical physics, mathematics, nonlinear science, etc. In order to improve the safety degree of pedestrian evacuation, the microscopic and macroscopic characteristics of evacuees get more and more attention of researchers.

The cellular automata could be used to model pedestrian evacuation for its characteristics of using simple local interactions to reveal the overall behavior and the time evolution of complex systems [1]. And the models are constantly being modified gradually by introducing new parameters or new pedestrian movement rules to model the crowd evacuation behavior and formulate routes decision-making for pedestrians accurately [2~7]. In recent decades, the concept of floor field was introduced into the pedestrian CA model to reveal the collective effects and self-organization encountered in pedestrian dynamics [8]. Many research efforts are obtained, such as the simplified floor field which is presented to focus on considering the distance between the exit and pedestrians [9,10], and the improved model containing some additional terms which take into account the interactions between pedestrian and surroundings, concerning the congestion near the exit [11], the psychology behavior of evacuees and the pedestrian distribution and so on[12].However, most of the above models have just studied on the specific evacuation behavior, without reflecting the route choice decision-making ability of crowd dynamically, therefore to cause the unreasonable route selection at times. And the former publications on the behavior of pedestrians had the intention to allow the well visibility, neglecting the impact of the visual sense on decision-making in evacuation process. The effect area [13] is introduced to take into consideration the spatial density of evacuees near the exit. However, the static area is inconsistent with reality.

In this paper, the visual field is proposed to reflect the decision-making ability of pedestrian and investigate its influence on pedestrian dynamics. Meanwhile, the efficiency of the model is analyzed through the contrast simulation experiment results. We shall proceed in the following way. In the first place, the extended model for simulating the pedestrian behavior is described in detail in Section 2. Meanwhile, the decision-making behavior rules are presented in Section 3, considering the effects of the visual function and other environmental factors. Moreover, the simulation experiment and the results are analyzed, and the critical values of parameters introduced in model are obtained in Section 4. In the end, the conclusion is given in Section 5.

2. Model Fundamentals

2.1. Cellular Automata Description

Cellular automata adopts space grid modeling with the appropriate neighborhood selection, combining the simulation of discrete time in order to improve the ability of the computer to simulate a large number of individuals. And n -dimensional cellular automata can be defined as follows:

$$C = (D_n, S, N, f), \tag{1}$$

where C represents a cellular automaton system; D_n is n -dimensional Euclidean space; And n is a positive integer, indicating the dimensions of the cell; S is a finite and discrete set of states, and the state of the cell in the lattice r at time t is defined by

$$S(r,t) = \{S_1(r,t), S_2(r,t), \cdots, S_k(r,t)\}, \tag{2}$$

where $S_k(r,t)$ can be interpreted to be the k^{th} state of the cell in the lattice r at time t ; N is the neighborhood domain of the center cell r ,which is the finite sequence subset of D_n . N is define by

$$N = \{N_1, N_2, \cdots, N_u\}, \tag{3}$$

where N_u denotes the position of the u^{th} neighborhood; The transform rules for $S(r,t) \to S(r,t+1)$ are given by

$$f = \{f_1, f_2, \cdots, f_m\}, \tag{4}$$

where f_m is the m^{th} partial conversion function in the cellular space, and the conversion rules of next step can be given by

$$S(r,t+1) = f_j\left(S(r+N_1,t), S(r+N_2,t), \cdots, S(r+N_q,t)\right), \ j = 1,2,\cdots,m, \tag{5}$$

This term reveals the characteristic of the cellular automata theory that the cellular state of the next time step is only related to its current state of the neighbors.

A two-dimensional Moore neighborhood [14] cellular automata model is presented in this paper (see Figure 1).

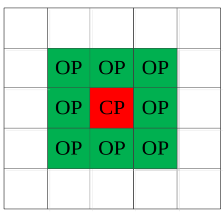


Figure 1. Moore Neighborhood Model

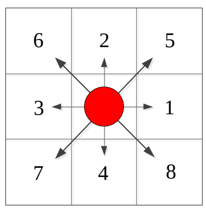


Figure 2. Optional Directions

CP means the current position while OP means the optional position, and the center cell in current position has eight optional movement directions next step (see Figure 2).

The cellular state of the next moment is determined by the evolving rules of cellular automata model dynamically, which is just the soul of the cellular automata. Hence, the more reasonable design of evolution rules could reveal the essential characteristic of the objective things accurately.

2.2. Floor Field Description

It is known that pedestrians would adjust their routes continually according to the state of the surroundings, in order to escape from the initial position to the final destination as quickly as possible. Sometimes, they will choose the optional position which is closest to the exit at next time step. Floor field [15] is introduced to describe the attraction of the architectural structure. In the previous model, center cell is assigned constant value according to the degree of approximation between the areas in which the cell and the exits are, which would lead to the unrealistic polyline route of the pedestrian in evacuation from the room with wider exit because of the same advantage of OP cells (see Figure 3).

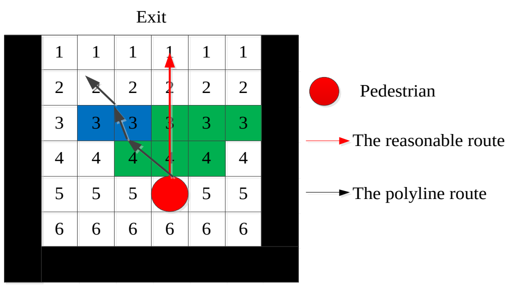


Figure 3. The Polyline Route Towards the Wider Exit

New method [16] is descripted that each cell would be given a constant value representing its distance to the exits, the smaller the value is, the stronger the desire of pedestrians to move toward the cell is. However, the reciprocating route appears near the big obstacle (see Figure 4).The pedestrian in the CP cell moves to the OP cell according to the floor field value assigned, but the pedestrian would return to the former position near the obstacle next time step, just because the CP cell has the shorter distance to the exit.

Figure 4. Reciprocating Route Near the Big Obstacle

The reciprocation parameter α is introduced to record the times of the cell occupied by every pedestrian. The probability of the cell to be chosen reduces due to the times of the cell used increasing. For example, $\alpha = 1$ indicates that it is the first times for the pedestrian to go through the cell, where $\alpha = 0.3$ states that it is the second times for the cell occupied by the same pedestrian, namely he or she has chosen a reciprocation route probably, especially when the cell exists near the big obstacle. While $\alpha = 0$ means no probability for the cell to be selected. In this paper, the floor field value F_{xy} of every cell is computed as follow:

$$F_{xy}=\begin{cases}\min\limits_{m}\left(\min\limits_{n}\left(\sqrt{\left(x-x_n^m\right)^2+\left(y-y_n^m\right)^2}\right)\right) & \textit{the cell apart from the obstacle or wall,}\\ \eta\min\limits_{m}\left(\min\limits_{n}\left(\sqrt{\left(x-x_n^m\right)^2+\left(y-y_n^m\right)^2}\right)\right) & \textit{the cell next to the obstacle or wall,}\\ Z & \textit{the cell } \text{occupied by } \textit{obstacle or wall.}\end{cases} \quad (6)$$

Where (x, y) is the coordinates of current cell location, (x_n^m, y_n^m) is the coordinates of the n^{th} cell in the m^{th} exit, and Z is a large positive number indicating that there is almost no attraction to pedestrians; η is collision avoidance parameter with $\eta > 1$, which describes the self-protection awareness of the pedestrian.

Evacuation pedestrians have the purposes to move towards the exits, and they would like to select the shortest straight path to evacuate as quickly as possible. Therefore, the concept of movement payoff P is introduced to denote the relative advantages obtained by the pedestrian movement. And the direction factor D is introduced to indicate the degree of approximation between the OP cell and the exits with a single step in a time step. A matrix of payoff $P = (P_i)$ is established by

$$\begin{bmatrix} P_6 & P_2 & P_5 \\ P_3 & P_0 & P_1 \\ P_7 & P_4 & P_8 \end{bmatrix}. \quad (7)$$

And the direction factor movement payoff P of the direction factor D is given by:

$$P(D_{ij})=\frac{F_{00}-F_{ij}}{(F_{00}-F_{\min})\sqrt{i^2+j^2}}, (i^2+j^2\neq 0; i=-1,0,1; j=-1,0,1) \quad (8)$$

Where F_{00} is the floor field value of the CP cell, and F_{ij} is the floor field value of the OP cell (i, j), $F_{\min}$ is the minimum value of F_{ij}. The positive movement payoff $P(D_{ij})$ obtained illustrates a situation that the pedestrian choose a closer position to the exit, while the negative $P(D_{ij})$ shows that the OP cell is farther from the exit.

Some certain cells in the eight OP directions might be occupied by pedestrians or obstacles. And the evacuees cannot move into the cell occupied. Thus, the empty factor describes whether the cell is occupied or not, which is given by

$$E_{ij}=\begin{cases}1 & \textit{the empty cell,}\\ 0 & \textit{CP cell,}\\ -1 & \textit{the occupied cell.}\end{cases} \quad (9)$$

And the movement payoff P of the direction factor E_{ij} is given by

$$P(E_{ij})=\frac{E_{ij}}{\sqrt{i^2+j^2}}, (i^2+j^2\neq 0; i=-1,0,1; j=-1,0,1). \quad (10)$$

Pedestrian could choose the route according to the maximum value of the movement payoff P in the evacuation process. However, the judgment and choice of evacuees are also affected by the complicated factors actually, such as the perception effect, environmental factors and so on.

3. The Decision-making Behavior Rules

3.1. The Visual Effect on Decision-making

At least 80 percent of the information of the external objects can be absorbed by normal crowds through their visual sense, including the size, shade, color, *etc*. Therefore, visual effect plays the important role on the decision-making process in pedestrian evacuation, which cannot be ignored [17].In addition, people would like to choose the familiar route or way relatively when the exit attraction plays as the leading role. Collection phenomenon will rise while the pedestrian cannot know the evacuation surroundings well. The shortest distance from the CP cell to the exit and the effect of the congestion density are considered in the former model. However, the congestion area was not defined concretely or reasonably.

The visual factor V and the dynamic visual field are introduced to describe the decision-making behavior of pedestrian in evacuation process. The visual field is divided into five parts (see Figure 5), and the two small parts are developed because of the characteristic of the imaging blind spot in field of the split vision. Meanwhile, the visual radius R denotes the size of the visual field. Moreover, the perception parameter λ indicates whether the exit is in the ken or not. When people could see the exit, $\lambda_{ij}=1$ represents that pedestrians are familiar with the environment, and they could choose the reasonable route depending on the high movement payoff, considering the distance from the exits, the occupant density, and the architectural structure. Otherwise, $\lambda_{ij}=0$ leads to the aimless collection phenomenon because of the panic mentality.

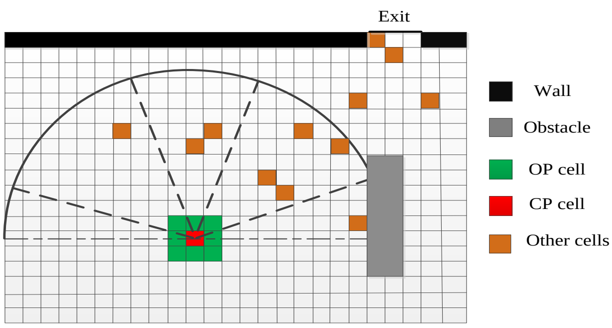


Figure 5. Five Sections of the Visual Field

The movement payoff P of the visual factor V is given by

$$P(V_{ij}) = \max_{m}\left(\max_{n}\left(\frac{d_m \cdot \rho_{in}^t}{d_L \cdot \rho_m^t}\right)\right), \tag{11}$$

where d_m is the width of the m^{th} exit in the visual field, d_L is the sum of all the door widths, and ρ_m^t is the density of pedestrian in the part of visual field where the exit exists in at time step t, meanwhile, ρ_{in}^t is the sum of pedestrian density in the visual field at time step t, with

$$\rho_m^t = \frac{N_m^t}{A_m^t},$$

and

$$\rho_{in}^t = \frac{N_{in}^t}{A_{in}^t},$$

where N_m^t is the number of pedestrians in the section of visual field in which the m^{th} exit exists at time step t, and A_m^t is the area of the section in the visual field in which the m^{th} exit exists at time step t. Moreover, N_{in}^t is the total number of pedestrians in the visual field at time step t, and A_{in}^t is the total area of the visual field at time step t.

Focusing on the collection phenomenon, the collection factor C is introduced to describe the collection behavior caused by anxiety and panic psychology of the evacuees for $\lambda_{ij}=0$. The movement payoff P of the collection factor C is defined by

$$P(C_{ij}) = \frac{N_i - N_{\min}}{N_{\max} + \sqrt{i^2 + j^2}}, (i^2 + j^2 \neq 0; i = -1, 0, 1; j = -1, 0, 1), \quad (12)$$

where N_i is the number of pedestrians in each section of visual field respectively, and $N_{\max}$ is the maximum value of N_i , while the $N_{\min}$ is the minimum value of N_i .

In summary, the movement payoff P of the cellular automata model based on floor field is given by

$$P = W_1(\alpha(\mathrm{P}(D_{ij}) + \mathrm{P}(E_{ij}))) + W_2(\lambda_{ij}\mathrm{P}(V_{ij}) + (1 - \lambda_{ij})\mathrm{P}(C_{ij})), \quad (13)$$

where W_1 and W_2 are the weight coefficients with $W_1 + W_2 = 1$. The reasonable OP cell will be occupied at every time step according to the value of the movement payoff. Simply put, the higher the value is, the stronger the desire of pedestrians to choose is.

3.2. The Solution of the Confliction

The confliction phenomenon of pedestrians could be simulated based on the above model due to the potential same movement payoff value of the target cell for two or more CP cells. In this situation, the extra movement payoff of every pedestrian reaching the target position is given by two effects.

First by the visual field, one will be more competitive when the object in his visual field in fact. Therefore, the competitive parameter β_{ij} is introduced, and $\beta_{ij} = 1$ indicates that the target cell is in the visual field of the cell (i, j) , while $\beta_{ij} = 0$ denotes cell (i, j) moves with no competitive power.

Second by the distance between a pedestrian and the target cell, and if conflicting cells gain the same value of competitive parameter β_{ij} , the closer to the target cell, the higher payoff to gain. The payoff of confliction is given by

$$P_{ij} = \beta_{ij} + (2 - \beta_{ij})\mathrm{Q}_i, \quad (14)$$

with

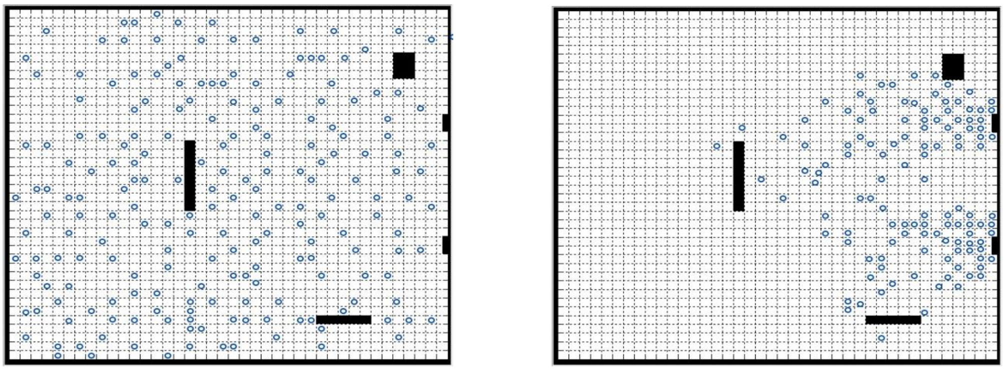
$$Q_i = 1 - \frac{\Delta d_i}{\sum_{i=1}^{r} \Delta d_i},$$

where Δd_i is the distance from the i^{th} pedestrian to the target cell; r is the number of pedestrians who expect to enter the target cell.

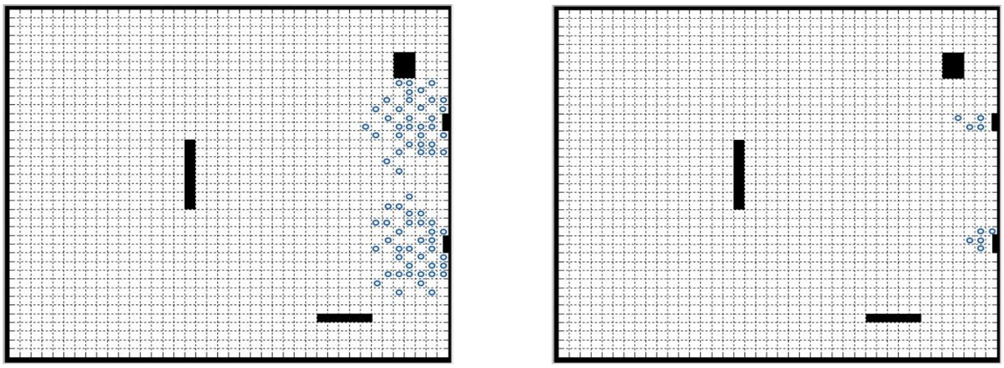
The pedestrian evacuation will be simulated based on the above model from a room with multiple exits with all the rules applied to all the pedestrians at every time step. And the parallel update of rules is adopted.

4. The Simulation Results and Analysis

The movement area in the room is marked out on a two-dimensional discrete grid in the model with the time domain discretized into a series of finite time steps Δt . The system size is 40, and every discrete cell has the same size $0.5m$ [18].Pedestrians can only move the length of one cell within every time step with the intended velocity $v = 1m/s^2$ [19], which results in $\Delta t = 0.5s$ .The total number of the evacuation pedestrians is 200, and the width L of every exit is given by $L = 1m$ .The typical stages of the dynamics of pedestrians evacuation are obtained (see Figure 6).



(a) t=0, the Number of Current People:200 (b) t=50, the Number of Current People:120



(c) t=100, the Number of Current People: 70 (d) t=160, the Number of Current People:9

Figure 6. Typical Stages of the Dynamics

4.1. The Comparison Results

In order to analyze feasibility and superiority of the improved model, we compared it with the previous model under condition of the same settings. 20 times simulation experiments were conducted and the mean value were taken for statistical analysis to obtain the evacuation time of all the models (see Figure 7).

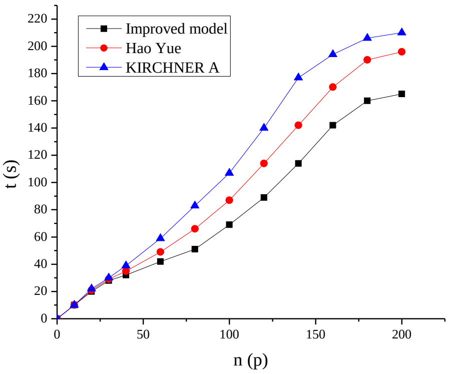


Figure 7. The Evacuation Time of Different Floor Field CA Models

As is shown in Figure 7, the improved model in this paper reduces the evacuation time and increases the efficiency of the evacuation. The calculation method of the floor field value is improved to solve the problem that pedestrians may deviate from the reasonable route in the process of evacuation from the room with the wider exit. Meanwhile, the reciprocating trajectory of pedestrians, which results from the plausible floor field values of the cell near large obstacles is avoid by adding reciprocation parameter α .That makes the strategy of evacuees to select route more reasonable and efficient.

Focusing on the psychology behavior of pedestrians, the collision avoidance parameter η is introduced in the model to describe the self-protection awareness. Empirically, pedestrians usually keep a distance from the obstacles existing in the way. As is shown in Figure 6, evacuees evaded the risk from obstacles or wall, when they were far from the exits. However, some pedestrians chose to ignore the safe distance from the obstacles because of the fearful attraction of the exits, namely the movement payoff in the mode. And the number of people who chose to touch obstacles changed with the different values of η in the simulation, as is shown in Table 1.

Table 1. The Number of People who Ignoring the Safe Distance against Different η

η	1	1.2	1.4	1.8	2
n/p	86	37	9	2	0

Where $\eta = 1$ describes that evacuees choose route regardless of the safety distance from obstacles, while $\eta = 2$ indicates that all the pedestrians who keep the self-protection awareness could neglect all the attraction of exit forever. Both of them are not realistic, so it is more reasonable where η varying from 1.2 to 1.4 .

4.2. The Effect of the Visual Field

In this section, we will analyze the dynamic decision-making behavior of pedestrian in the process of evacuation by visual factor V and the divided visual field on the basis of the Moore neighborhood cellular automata model, taking into account the surroundings in the visual field of pedestrians, including the distance from the exit, the pedestrian density, building structure and so on. It is well known that the size of the visual field has played the important role in pedestrian decision-making. The broader the visual field is, the more familiar with the surroundings the evacuee is. The effect of different vision field radius R on evacuation time were simulated and the experiment results were obtained(see Figure 8).

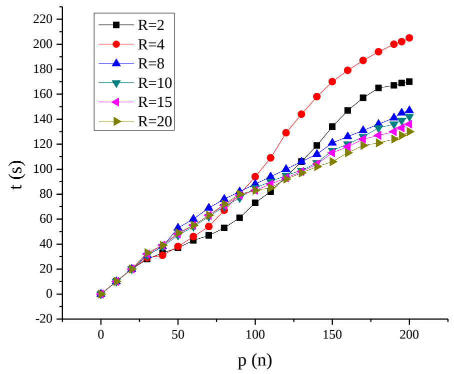


Figure 8. The Evacuation Time against the Different R

As is shown in Figure 8, in the conditions of $R = 2$ and $R = 4$, pedestrians spent more time to evacuate, which interprets the fact that the degree of familiarity with the surroundings directly influences pedestrian to decide and choose the escape route. When the size of visual field is small, such as $R = 4$, the unknown panic psychology often leads to collection phenomenon. Both the pedestrian jam and the polyline route deviating from the shortest path have cost more evacuation time. And it takes less time in the condition of $R = 2$, probably because of the low degree of sensitive to the high density of the pedestrians nearby, and it has more advantages to choose the shortest path towards the exit in the process of evacuation according to the floor field.

However, when the size of visual field is bigger, such as $R = 8$, evacuees could make the reasonable decision dynamically in time, according to the distance to all the exits in their visual field, the width of the exits and the surrounding density of pedestrians to shorten the evacuation time. The evacuation time trends of the four conditions, namely $R \geq 8$, are similar because of the limit of the system size.

In order to illustrate the impact of visual field on evacuation further, the simulation for utilization rate of exits against different R was carried out in this paper (see Figure 9). The balanced utilization coefficient ω is introduced to represent the utilization rate of two exits in the evacuation process. And ω is given by:

$$\omega = \frac{\left| N_1 - N_2 \right|}{N_1 + N_2} , \qquad (15)$$

where N_1 and N_2 are the number recorded of the pedestrians who have evacuated through two exits respectively.

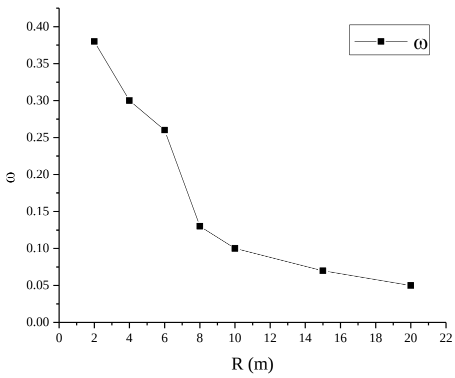


Figure 9. The Balanced Utilization Coefficient ω against Different R

According to the definition, the assumption $\omega = 0$ indicates that the two exits are balanced used and the evacuation time would be shortened, it turns to be the best solution. However, the simulation results show that when the radius of visual field was given by $R = 2$, the utilization rate of exits is low, which makes the evacuation pedestrians at a disadvantage. With the increase of vision radius R , the utilization rate of exits is improved at the same time, which reflects the healthier trend for pedestrian evacuation.

Meanwhile, it also conforms to the assumptions proposed [20] that the evacuation behavior of crowd is the complex behavior, which integrates individual behavior and conformity behavior. If the pedestrians are sensible, when the incident broke out, they could evacuate effectively and safely.

4.3. The Exit Condition

Pedestrians will spontaneously take different evacuation strategy to adapt to the changes of surroundings based on the above decision-making behavior rules. Therefore, the effect of the environmental condition such as the exit conditions should be discussed in this section, including the width L and the layout of two exits (see Figure 10). Keep the initial conditions for the simulation besides $R = 8$ and $\eta = 1.4$ .Moreover, the distance S between two exits is introduced to represent the layout of the exits on the same wall.

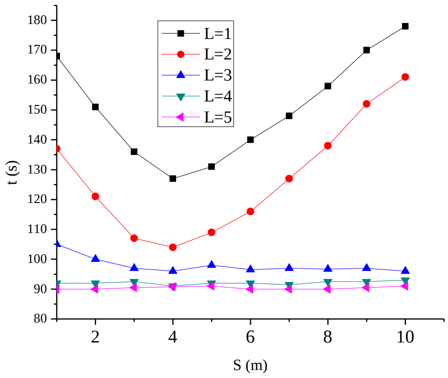


Figure 10. The Evacuation Time for Different Exit Width and Layout

As is shown in the figure, the evacuation time decreases obviously with the increase of the exit width in the initial stage, where L varyed from $L = 1$ to $L = 2$ for example. It is consistent with the actual situation that the wider exit increaes the pedestrian flow rate in the evacuation process to avoid queuing and congestion near the exit. However, the utilization rate of the exits has reached saturated value when the exit width reachs to a certain degree,such as $L = 3$, because of the finite system scale, and it takes little effect on the evacuation time even if the exit width increase gradually. Therefore, there is the optimum width L which can improve the efficiency of the evacuation.

In the same time, the optimal layout of the two exits is obtained by simulation based on the above model with the critical value $S_0 = 4$ .On the one hand, when $S < S_0$, because of the narrow space between two exits, the congestion of pedestrians is caused near the exits by the chaotic crowd consisted of two pedestrians flow who choose the two exits as the target position respectively. On the other hand, when $S > S_0$, because of the relatively spacious space between two exits, the pedestrian cannot find two exits in his or her visual field at the same time, who would rather queue up in front of the nearer exit, without the decision-making for the reasonable route. There is no doubt that the low utilization rate of the exits delays the evacuation time. Moreover, most of pedestrians cost more time to reach the remote exit of the room to extend the evacuation time.

5. Conclusions

In this paper, the decision-making behavior rules based on the improved floor field CA model is established to describe the walking behavior of pedestrians. The dynamic factors are introduced to describe the judgment of pedestrians on the surroundings, which make our model successfully capture the characteristics of decision-making behavior of pedestrians. Meanwhile, the psychology behaviors of the pedestrian have been simulated by the perception parameter and the collision avoidance parameter. It can be concluded that the psychology behavior of the pedestrians would change accordingly along with the adjustment of decision strategies generated in the evacuation process. Moreover, the effect of visual radius is discussed by simulating the evacuation time and the utilization rate of exits. The optimum width and layout of the exits are obtained from the simulation results and the analysis. The improved model can produce the more realistic outcome by the dynamic decision-making rules to provide guiding significant information for designer to evaluate pedestrians and optimize the building structure. In following studies, the author would process some complex cases such as the effect of interference factors on the speed of pedestrians to further improve the behavior rules and the algorithm.

Acknowledgments

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