A cellular automaton model with varied walk velocity

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Abstract: This paper presents a new cellular automaton model in which the neighborhood is the extended Moore's neighborhood($r = 2$) and each cell's walk velocity is the function of inter-person distance. This model can simulate pedestrian movement with different velocity through letting pedestrian move more than one cell. In the evacuation process, the moving rules are determined by three functions: exit function, direction function and velocity function. An emergency evacuation example is used to illustrate the validity of the new presented varied walk velocity cellular automaton. Comparing the results obtained by the non-varied walk velocity cellular automaton model and the new model, it is demonstrated that the new model is more valid to simulate evacuation and the evacuation time is shorter.

Key–Words: cellular automaton, evacuation, varied walking velocity, updating function, extended Moore's neighborhood, simulation

1 Introduction

Evacuation can be possibly caused by earthquakes, building fires and flood, etc. Great losses will be caused if the crowd could not evacuate successfully. In order to minimize their exposure to hazards, the crowd should evacuate successfully. Effective evacuation plan is of great importance. In the last few years, many researchers used mathematical and physical tools to study evacuation problems. The exiting models can be divided into two categories. The first one is the theoretical research.Reference [1] studied four factors which affect the evacuation time. These factors are building structure, disaster environment, personal physical condition and educational experience. Smith [2] studied the relationship between pedestrian's density and velocity, and obtained a formula expression between them.

The second category is the simulation models. One of the popular models is the cellular automaton. Some researchers studied the influences of exit choice factors to the evacuation time including the width and position of exits, personnel psychology, obstacles etc [3-12]; Yonggui [13] changed the cell shape from square to rhombus. This can effectively stop pedestrians to move against walls or obstacles; Other studies are about the applications of these numerical models to some evacuation problems for special disasters including fire, earthquake and flood [14-15]. Most of the evacuation simulations using cellular automaton introduced above are based on the assumption that every pedestrian has the same walk velocity and each pedestrian's walk velocity is considered non-varied. For simulating the pedestrian movement with different walk velocities. Kirchner et al [16] investigated the influence of the interaction range and the spatial discretization. However, in their pedestrian simulation, there is only one kind of pedestrian, i.e., all pedestrians with the same walk velocity in spite of high or small walk velocity. In reference [17], there are four kinds of walkers including the right walkers with walk velocities 1.0 and 1.5m/s moving from the left to the right boundary. The same kind of people move with the same velocity. In one emergency evacuation, every pedestrian's walk velocity mainly depends on pedestrian's density, human emotion and surrounding status around each of them. And it is always varied. So, people move with varied velocity in the simulation model is of great importance. This is the main objective of this paper.In this paper, the neighborhood of the cell is the extended Moore's neighborhood. Pedestrian's walk velocity is function of inter-person distance. The evacuation time of every person depends on multiple factors including its position, its distance to exist, exits congestion and exits evacuation capability. All these factors are considered to obtain a more valid model. On the above basis, cellular automaton model with varied walk velocity is presented. In the same situation, evacuation is simulated respectively by traditional non-varied velocity cellular automaton model and the proposed model for a same evacuation example. The results show that cellular automaton model with varied walk velocity can be used to simulate emergency evacuation more practically and the evacuation time is shorter. Another simulation is done in order to describe the evacuation more actually. The fire disaster is included in the evacuation environment based on the above model. This is also a compare between the original environment and the environment including fire disaster. Also the best capacity of people in the evacuation environment is computed.

In section 2 we introduce the main concepts of the CA model and three functions used in the simulation model. This section also includes the varied walk velocity CA model and simulation program. In section 3, we describe our simulation work in two situation. In section 4, we discuss the performance of the new model, the strengths and limitations of our approach.Conclusion and the possible future extensions is in section 5.

2 Cellular automaton model with varied walk velocity

2.1 Cellular automaton

The cellular automaton is widely used and it is studied deeply by researchers,such as in references[18]-[21]. Cellular automata is a dynamical system with discrete values in space,time and state.The underlying structure is a $m \times n$ cell grid, where$m \times n$ is the system size. Each grid is occupied by obstacles, or by one pedestrian or empty. The neighborhood considered in the model is Moore's neighborhood, that includes the eight cells surrounding the central cell if $r = 1$ (see Figure1). But in our new model the neighborhood is extended Moore's neighborhood. Equivalent to description of Moore's neighborhood above, but neighborhood reaches over the distance of the next adjacent

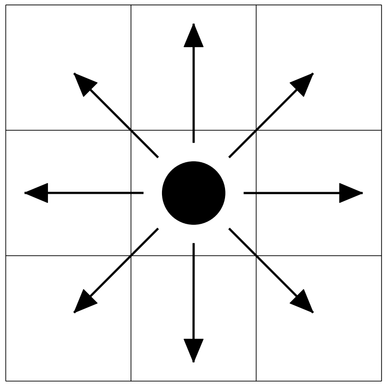


Figure 1: Moore's neighborhood $r = 1$

cell. That is $r = 2$. With this choice it aims to provide each individual in the system with all 32 movement direction. (see Figure 2). It is assumed that all pedestrian choose a cell as a target grid in the next time-step according to the following three updating function.

2.2 Three updating function

2.2.1 Exit function $f(x, y)$

Exit function is used to define the exit chosen by a pedestrian which can be written as follows

$$f(x, y) = \lambda_1 d + \lambda_2 a + \lambda_3 b$$

where d indicates the Euclidean distance between a cell with coordinates (x, y) (in meters) and one of the exits ; a indicates number of pedestrians around each exit; b indicates exit blocking factor which reflects evacuation capacity of an exit (defined as the reciprocal of exit width); $\lambda_1, \lambda_2, \lambda_3$ are weights respectively. The function value is the exit code. Specifically, the center coordinates of each exit are $(x_1, y_1), (x_2, y_2), \cdots, (x_n, y_n)$. Number of people randomly distributed around exits is $a_1, a_2, \cdots, a_n$ respectively. Select appropriate weighting coefficient $\lambda_1, \lambda_2, \lambda_3$, the function value

$$f_i(x, y) = \lambda_1 d_i + \lambda_2 a_i + \lambda_3 b_i (i = 1, 2, \cdots, n)$$

can be calculated .

If $f_k(x, y) = \min\{f_i(x, y), i = 1, 2, \cdots, n\}$, then the k-th exit is selected. That means, by comparing the distance, the exit congestion and exit width to determine which exits pedestrian should select.

2.2.2 The direction function

Direction function is used to define the walk direction of the pedestrian. Specifically, find neighbors in inner

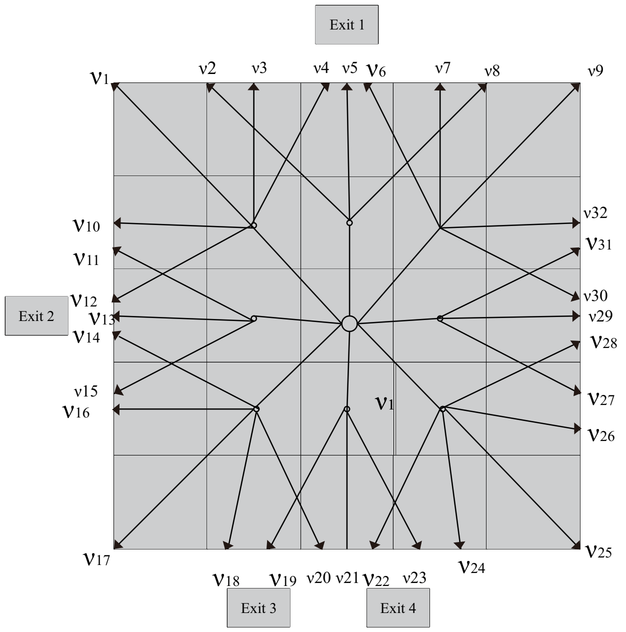


Figure 2: Extended Moore's neighborhood $r = 2$

layer and outer layer in the same direction. If they are all unoccupied then this direction can be chosen. The neighbor in inner layer is unoccupied but the neighbor in outer layer is occupied then this direction can be chosen too. There may be several cells $c_1, c_2, \cdots, c_n$ are empty and can be the next target grids. Compute the distance d_i between the empty cells $c_1, c_2, \cdots, c_n$ and the k-th exit. If $d_j = \min\{d_i i = 1, 2, \cdots, n\}$, then the j-th cell c_j is the target grid. So the number of moving grids is known. This is also the moving distance.

The direction code is defined as the value of the direction function. In this way, each pedestrian calls its own direction function and knows the next moving direction. If the selected exit direction is not the same as direction determined by the exit function, then the pedestrian will have to stay in place.

Specifically, as shown in Figure 2: the four exits codes are A_1, A_2, A_3, A_4, eight direction codes which pedestrian can choose are $v_1, v_2, \cdots, v_{32}$. If the pedestrian chose exit A_1 by exit function, but the direction is one of $v_{17}, v_{19}, \cdots, v_{25}$ selected by direction function.That means the two directions are deviated and the cell does not move. If two or more pedestrians try to move to the same cell, only one randomly chosen pedestrian is allowed to move forward to this site. This is the easiest way to incorporate the concept of friction [22].

2.2.3 Velocity function

Velocity function is used to define the walk velocity of pedestrian. We consider the main factor affecting walk velocity is inter-person distance and establish the relationship between them.The inter-person distance is defined as the distance between the centers of the bodies of two individuals.

Since the desire that pedestrians change velocity is relevant to their current velocity v. A pedestrian who wants to get ahead with a desired maximum velocity v_m will accelerate if his or her actual velocity v is below v_m. So relative velocity change rate $\frac{1}{v}\frac{dv}{dx}$ is in direct proportion to potential growth of velocity $[v_m - v(x)]$. The pedestrian's walk velocity can accelerate quickly if the inter-person distance is far. So $\frac{1}{v}\frac{dv}{dx}$ is in inverse proportion to x. Let β^{-1} is the corresponding proportion coefficient, β can be regarded as a measure of panic or irrationality in the behavior of pedestrians. The better psychological quality; the bigger, value of β. Establish the following differential equation.

$$\frac{1}{v}\frac{dv}{dx} = \beta^{-1}\frac{v_m - v}{x}$$

Solving the above difference equation. We can get the relationship between velocity and inter-person distance as follows:

$$v(x) = \frac{v_m (cx)^{\frac{v_m}{\beta}}}{1 + (cx)^{\frac{v_m}{\beta}}} \tag{1}$$

The parameters are computed from data fitting. The data used here is from reference [23]. Fitting equation is equation (1) . Fitting curve is shown in Fig3. The corresponding parameters are $c = 1.1846$, $v_m = 1.2009$, $\beta = 0.17649$. And the correlation coefficient is $R = 0.9025$. The value of R is higher than the correlation coefficient in reference[23]

In order to compare the result with the previous result in reference [23] and reference[24] , Let

$$x = \sqrt{\frac{1}{\rho}}$$

and rewrite equation (1) to be the following equation:

$$v = \frac{v_m}{1 + (c^{-2}\rho)^{\frac{v_m}{2\beta}}} \tag{2}$$

We can get the fitting curve shown in Figure4. The parameters are $c = 1.1846$,$v_m = 1.2009$, $\beta = 0.17649$. And the corresponding relation coefficient

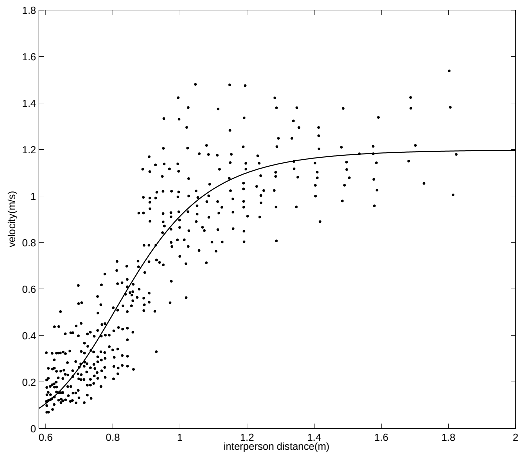


Figure 3: Data fitting curve of velocity equation

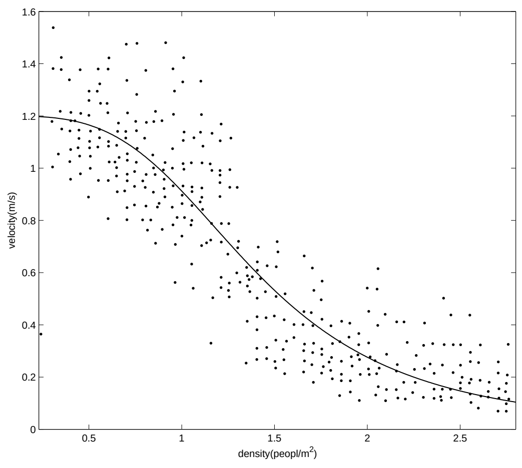


Figure 4: relationship between velocity and density

is $R = 0.9025$. It is easy to see that the fitting curve is similar to the curve in reference [24]

Cellular automaton is defined in a discrete place, in which cell can only move integer steps. But velocity calculated by velocity equation above is continuous. Difference is used to discretize the velocity equation

$$\frac{1}{v}\frac{dv}{dx} = \beta^{-1}\frac{v_m - v}{x}$$

The result is following equation:

$$\Delta v = v_{m+1} - v_m = \frac{1}{\beta x_n}(v_m v_n - v_n^2)\Delta x \qquad (3)$$

assume $\Delta x = 1$ then we get :

$$v_{n+1} = v_n + \frac{1}{\beta x_n}(v_m v_n - v_n^2) \qquad (4)$$

where x_n is inter-person distance, v_n is walk velocity at the n-th time step. The parameter $v_m = 1.2009m/s, \beta = 0.17649$, is from the above data fitting.

Compute distance between the centers of the bodies of two individuals in this direction. This distance is x_n. Walk velocity can be calculated by formula (4). The walk distance d is known, then we know the time $t = \frac{d}{v}$ corresponding to one time step.

2.3 cellular automaton programming

The updating programming of the model is described below:

(1) A certain number of pedestrians are randomly distributed in two-dimensional plane that we studied;

(2) Each pedestrian can choose exit by exit function;

(3) The moving direction and the target cell can be chosen by direction function;

(4) If the direction that determined by the direction function is not consistency with the exit direction determined by (2), the cell will not move, otherwise execute(5) ;

(5) Determine the number of steps according to velocity function and compute the corresponding time.

(6) After parallel updating of every cell during each time step, determining whether the pedestrian reached exit. If so, it is removed from the system.

(7) Repeat (2), (3), (4) (5) until all pedestrians walk outside.

Cell updating flowchart shows in Figure 5.

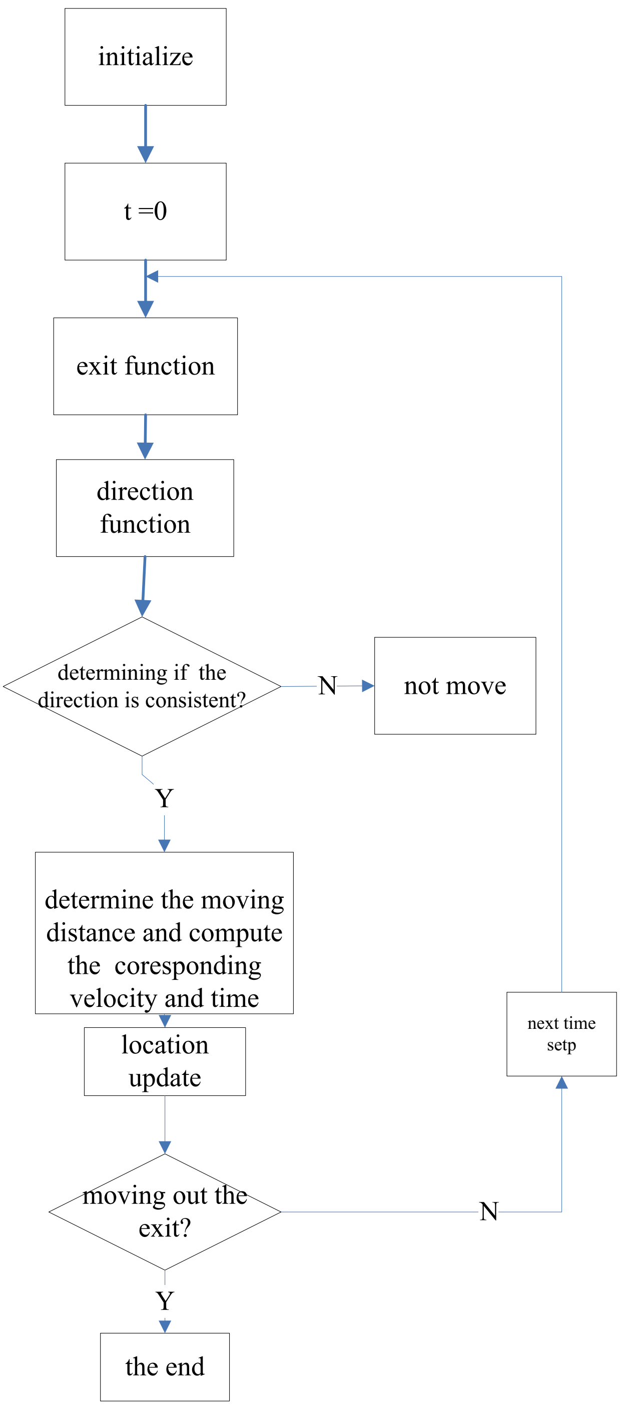


Figure 5: Cell updating flowchart

3 Simulation

The place is evenly divided into a 58×58 grid system in which each cell represents $0.5m \times 0.5m$ area. There are four asymmetric exits in the place (see Fig 2). Pedestrian can move into a cell only if it is empty.We carried out two simulations namely: simulation 1 and simulation 2. In simulation 1, pedestrian's walk velocity is non-varied, that is pedestrians move one cell each time step. In simulation 2, pedestrian's walk velocity is varied and calculated by (2). This is the only difference between simulation 1 and simulation 2. There are 800 people in the place. For comparison, the 800 people's locations in simulation 1, are the same as in simulation 2. Cells update in accordance with the above updating function.

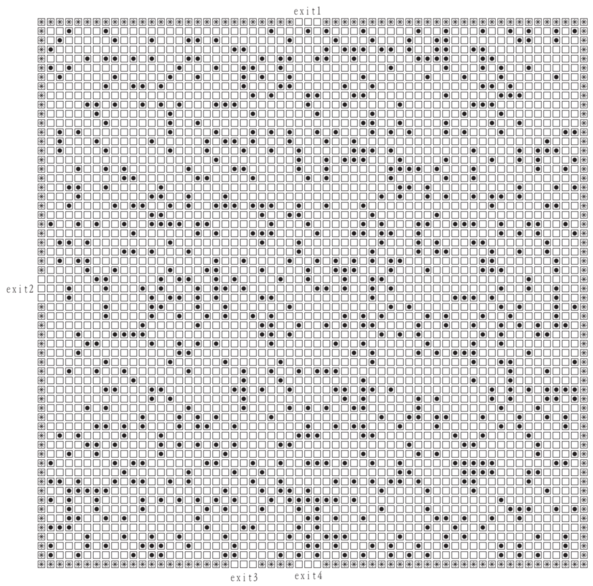
First, only simple situation is considered. The exits width are equal, that means they have the same blocking factor, $b_1 = b_2 = b_3 = b_4 = b$. According to usual habit of people, let $\lambda_1 = 0.4, \lambda_2 = 0.4, \lambda_3 = 0.2$. (Scientific method for choosing the value of $\lambda_1, \lambda_2, \lambda_3$ can also be studied. This is not studied in this paper.) Figure 6 shows the typical snapshot of evacuation with varied walk velocity. Four stages are observed: (a) beginning $t = 0$, (b) middle $t = 10$, and (c) $t = 25$, (d)final stage $t = 49$. Initially, the pedestrian can pass the exit smoothly. In the middle stage, the bottleneck is thoroughly formed around the exit. This situation will last until all of the people move out of the exit. When the number of people is relatively small, the evacuation process is smooth and there are no jams all over the calculation domain. The evacuation time step is recorded. In simulation 1 evacuation time is 104 time steps. In simulation 2 evacuation time is 76 time steps.

To examine further, we obtain the correlation between the number of people out exit and the total evacuation time step in simulation 1 and simulation 2. Figure 7 the people out of exit along with evacuation time steps.

It can be seen from Figure 7, it spends all persons less time to move out exit in simulation 2. The result is more consistent with reality. The path of the same pedestrian is recorded in simulation 1 and simulation 2 respectively (see Figure 8). The blue one is the pedestrian's path in simulation 2. The black one is the pedestrian's path in simulation 1. It spends 56 seconds for all pedestrian walk out exit in simulation 1 and 33 seconds in simulation 2. Time is shorter in simulation 2 .

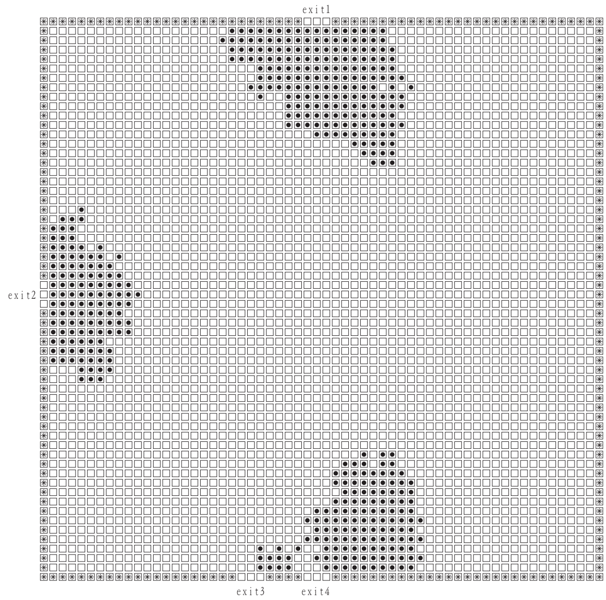
In order to compare the congestion of exit between simulation 1 and simulation 2, the number of people around exit1 is recorded in simulation 1 and simulation 2 respectively.(See Figure 9)

Another simulation is done in order to describe



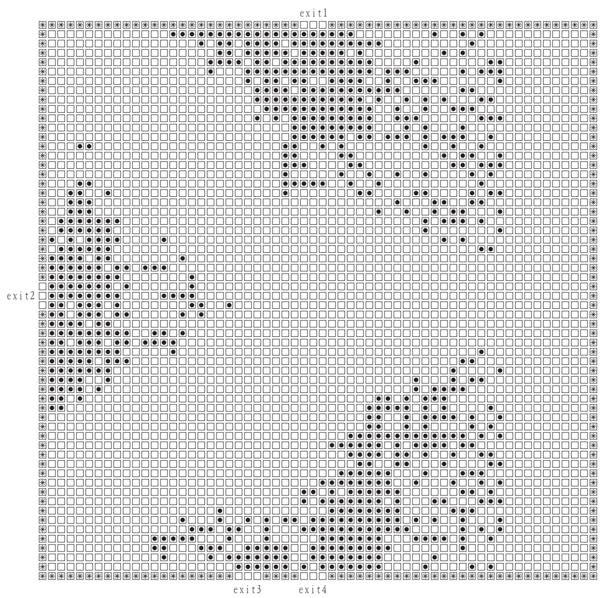
a (t=0)

Figure 6: Evacuation simulation in the place with four asymmetric exits. Four typical stages are shown.



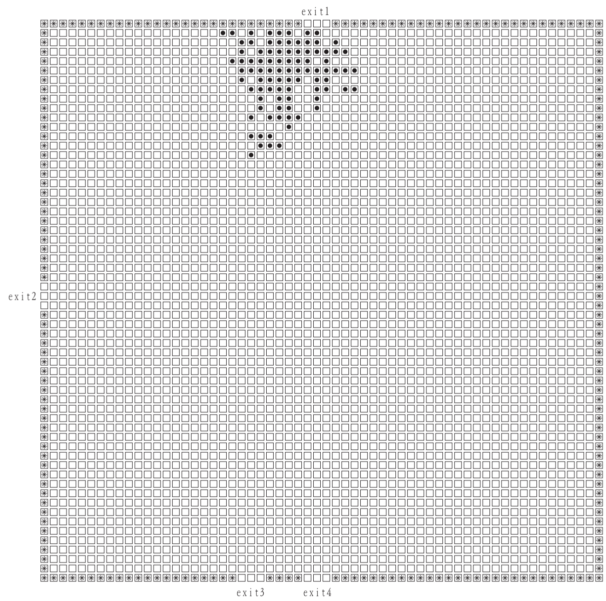
c (t=25)

Figure 6: Evacuation simulation in the place with four asymmetric exits. Four typical stages are shown.



b(t=10)

Figure 6: Evacuation simulation in the place with four asymmetric exits. Four typical stages are shown.



d (t=49)

Figure 6: Evacuation simulation in the place with four asymmetric exits. Four typical stages are shown.

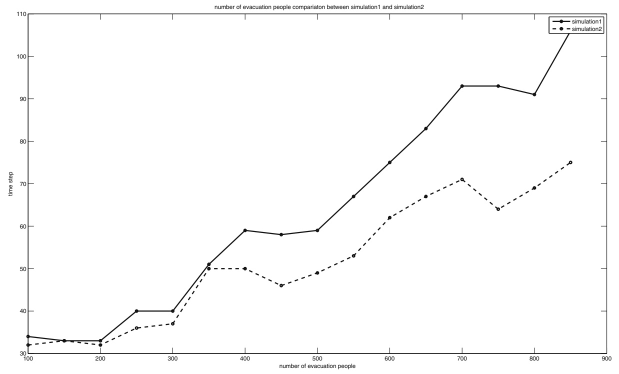


Figure 7: Comparison between non-varied velocity and varied velocity

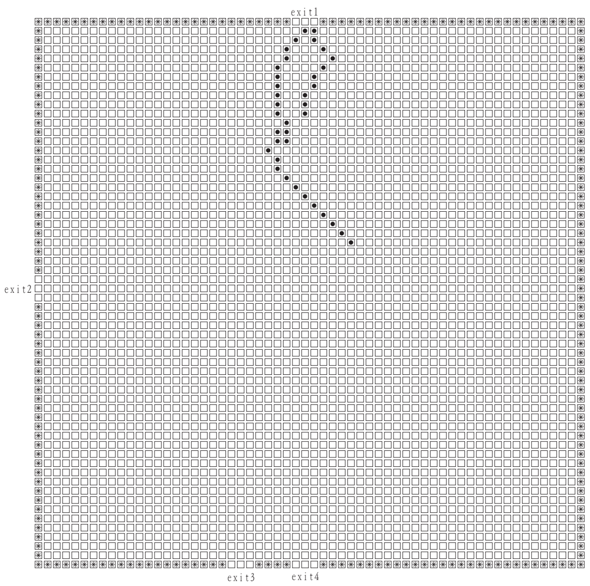


Figure 8: Path of the same person in simulation 1 and simulation 2

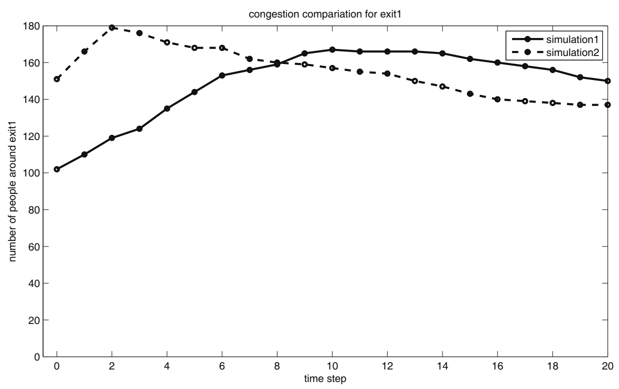
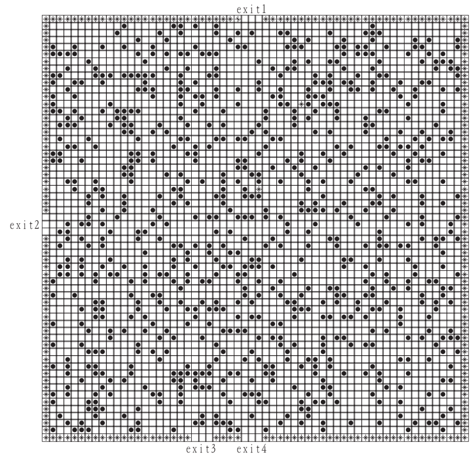


Figure 9: Exit1 congestion comparison in simulation 1 and simulation 2



a (t=0)

Figure 10: Evacuation simulation in the environment including fire disaster. Four typical stages are shown

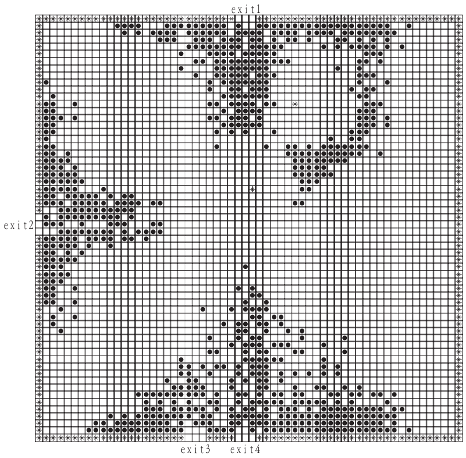
the evacuation closer to reality. The fire disaster is included in the evacuation environment based on the above model. This is also a compare between the original environment and the environment including fire disaster. The fire disaster source is set up in the evacuation environment.Fig 10 shows the typical snapshot of evacuation in the fire disaster environment. Four stages are observed: (a) beginning $t = 0$, (b) middle $t = 5$,and (c) $t = 40$, (d)final stage $t = 100$.

In order to compare the density of four exits and provide advice to the evacuation guide,the density curve of each exit is recorded(See Figure11).

The best capacity of people in a large public places is very important to the loss of control when there is a diaster.Figure12 shows evacuation time trend along with the evacuation amount in this environment. When evacuation amount is 400, the change rate of evacuation time increase quickly. So this is the threshold of congestion. When evacuation amount increases from 400 to 800, the evacuation time increased from 76 to 145. That is when evacuation amount increases double,the evacuation time increased nearly double. This shows that when the evacuation amount exceed the threshold, the congestion will be very serious. This can cause the evacuation time increasing quickly. Also the same method can be used to estimate the people number of other places.

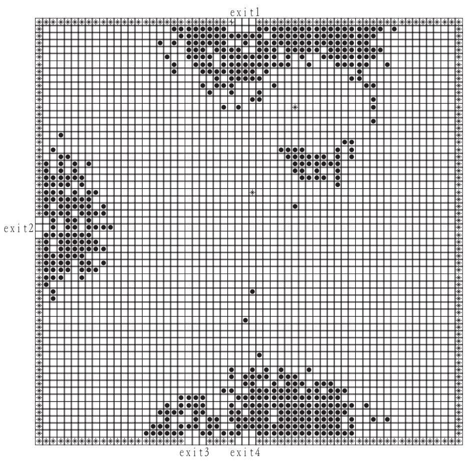
4 Results and Discussion

(1) From Figure 7 , it can be seen that the difference between two simulations is not obvious in initial time



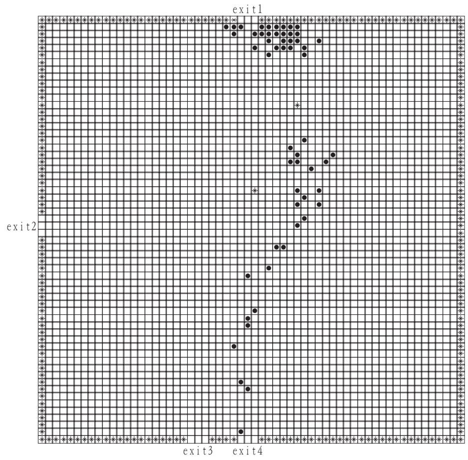
b (t=5)

Figure 10: Evacuation simulation in the environment including fire disaster. Four typical stages are shown



c (t=40)

Figure 10: Evacuation simulation in the environment including fire disaster. Four typical stages are shown



d (t=100)

Figure 10: Evacuation simulation in the environment including fire disaster. Four typical stages are shown

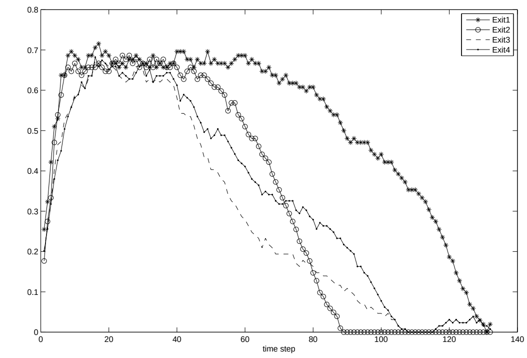


Figure 11: Density compare of four exits

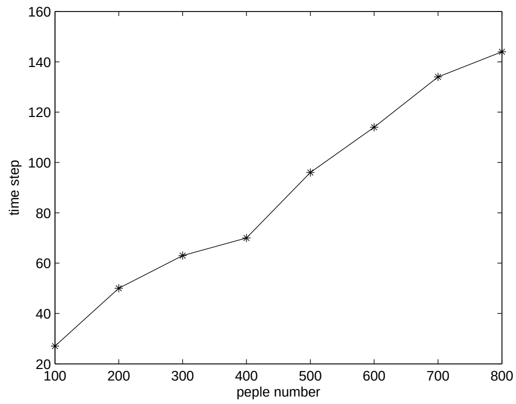


Figure 12: Evacuation time trend along with the evacuation amount

and the difference is gradually increased in late evacuation. It is because that people accumulated around exits early, so the walk velocity will not be too great. Then some people move out of exit, and people behind will be more and more quickly. At this time varied walk velocity played a role .This is more actually.

(2) Each cell's path can be recorded just like that shown in Figure 8 .It can be seen from the figure that the cell go outside more quickly in simulation 2. This is valid.

(3) From Figure 7, it can be seen that at the beginning the number of people around exit is increasing more quickly in simulation 2 than in simulation 1. With the evacuation going on, the number of pedestrian around exit is decreasing. Also number of people decreasing quickly in simulation 2 than in simulation 1. It is because that in simulation 2 pedestrian can walk more than one cell every time step. This is the difference from simulation 1.

(4) Figure 10 shows the evacuation process including fire disaster. It appears a circle around the fire. This is actually. At the final stage of evacuation, there are some people around exit1 but there are nearly no people around other exits. So this can provide guide to the evacuation.

(5) From Figure 11 we can see density trends of four exits are similar but a little different.It shows that density increased quickly at the beginning. At this time, people reached to exit gradually. People congested to the exits and waited for going out. Then density reached to peak and continued for some time. As people go out of the exits gradually. The density reduced . This is realistic. Density of exit1 is higher than that of other exits obviously. Density of exit3 is lower. It is because that the fire source is near exit1 and the exits are narrow. Evacuation complete earlier in other exits. This can provide suggestions for people to guide the evacuation and the evacuation time will be shorter.

5 Conclusion

The varied walk velocity cellular automaton model is presented. This model can simulate pedestrian movement with different velocity through letting pedestrian move more than one cell. The new model is more valid to simulate evacuation and the evacuation time is shorter.

It is hoped that the established model can be applied to provide guidance for establishing contingency plans in other public places.

This part is the next work we plan to do. We will study the evacuation process further from two sides based on the existing model in this paper. On the one hand, the evacuation logo will be set in the evacuation place. This can help people control the evacuation. We will do some simulation study considering the related factors in all cases. On the other hand, we will extend the simulation study to three-dimensional space such as buildings.

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