

# Simulation Model of Pedestrian Evacuation in High-Rise Building: Considering Group Behaviors and Real-Time Fire

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## Abstract

*Many fire evacuation models have been proposed in recent years to better simulate such as an emergency situation. However, fire has different characters in high-rise building, and is affected by all kinds of factors. Evacuation of persons in case of fire is very complex, the environment will be affected, the individual psychological quality and physical quality, real time fire and so on. The numerical model based on cellular automata is presented, considering group behavior and real time fire development in the paper, and simulation experiments show the model is on the brink of reality and demonstrate its applicability and validity.*

**Keywords:** *pedestrian evacuation, group behavior, real-time*

## 1. Introduction

In recent years, with the sustained and rapid economic development, China has most number of skyscrapers over the world. High-rise buildings have a lot of new characters, such as high wall, dense population, complex structure, long time to escape and so on [1]. Once fire takes place in these buildings, fire and fumes will spread rapidly which will result in a difficult evacuation and cause serious injury to human [2]. It is very difficult to make all personal evacuation when an emergency happens in high-rise building, especially fire. There are three main factors influencing the evacuation: the first one is that the evacuation distance is long and complex; the second one is that it is easy to crowd when large number of people assemble together; the last one is that the chimney effect is significant, in the vertical space fire and smoke spreads faster. Hence, sufficient attention should be paid on pedestrian crowds' evacuation in a high-rise building. A simulation of the process of pedestrians' evacuation from a high-rise building carried out in this paper.

Modelling of pedestrian evacuation from a building in a fire has been studied over the past decades. An agent-based simulation model for building evacuation was proposed by Owen M., Galea and Spengler J during a fire disaster, reckoning the fire dynamics and spatial change [3,4]. Tang, Fangqin, and Aizhu Ren applied an ant colony evacuation model that includes avoidance and preferential path selection behaviors, when a fire occurs in the high building suddenly [5]. Yamamoto proposed a multi-resolution agent-based model to simulate pedestrian flow in a fire disaster [6]. Blue VJ also investigates theoretical method and explains the evacuation competitive capacity for emergent large passenger flows in different height of buildings [7]. Jain et al. discovers the congestion features at the floor stairs of a building once a fire occurs [8]. R.D. Peacock considered influence of panic coefficient on evacuation, who takes social factors into account, but only considering a few factors. In the process of building fire evacuation, exits and stairs

are usually the bottleneck positions. Fire incident in a building always threatens human life [9]. S. Gwynne, E. R. Liang, A. Y., Low, Wooldridge M J had developed large number of approaches for the modelling of evacuation, among which the cellular automata (CA) was widely used [10,11,12,13]. E R, Owen M proposed a CA model based on simple human judgment to simulate bi-directional pedestrian movement [14]. Jason E. Floyd studied the dynamic characteristics of a counter flow with different walking velocities and boundary conditions [15]. C. Burstedde, K. Klauck applied a two-dimensional model for the simulation of evacuation with respect to kin behavior [16].

In current researches, on the one hand, pedestrian evacuation and fire scenarios usually are considered [17,18] respectively, which ignores the influence of fire environment in real-time on the pedestrian evacuation; on the other hand, group behavior is ignored [19, 20], person who is not familiar with the building will follow others and interact with each other. The real time fire will reduce the judging ability and mobility, delaying evacuation time and reducing the number of evacuation people. Meanwhile, following behavior also has disadvantageous influence on the pedestrian evacuation. Therefore, with considering the complex characters of high-rise building fire, we build an overall fire evacuation framework and the process of evacuation mode, which contains places and building structure, individual and group behavior and real time fire environment, and considering both important factors. Then a numerical model based on cellular automata is therefore proposed to study the group and fire development effect on evacuation. Finally, we implement two simulation experiments, and results show us that both the following behavior and real time fire have great influence on the pedestrian evacuation.

The rest of the paper is organized as follows. Section 2 gives a comprehensive introduction to the fire evacuation model we proposed and related basic theory knowledge, and then further discusses the crowd evacuation group behavior model and real fire situation in detail. In Section 3 simulation experiment is carried out to prove our model, and the results show us the effectivity. The conclusion and possible research trends are discussed in Section 4, finally.

## 2. The Fire Evacuation Model

### 2.1 Basic Knowledge of Cellular Automata

In the past decades, quite a number of approaches had been developed for the modelling of evacuation, among which the cellular automata (CA) was widely used [21] [22]. Cellular Automata was first proposed by Von Neuman and Ulam. Briefly, CA is a discrete dynamic composing of a regular grid of cells, each in one of a finite number of states. States, neighbourhood and update rules are the three core elements of the CA model. Namely, each cell is discrete; all the cellular states are synchronous changing. Basic update rules are as follows: the  $i$ th cell status in  $t+1$  time is determined, by both its status in  $t$  time and status of finite cells in its neighbourhood in  $t$  time simultaneously, clearly in the following formula:

$$S_{t+1} = f(S_t, N) \quad (1)$$

in which  $S$  is a finite state set for cells,  $N$  represents a combination of all cells in neighbourhood, as space vector which contains  $n$  numbers of different cells, expressed as  $N=(A_1, A_2, A_3, \dots, A_n)$ ,  $n$  is number of neighbour cell,  $f$  is the conversion function which makes  $S_t$  map to  $S_{t+1}$  state. CA is used to simulate a dynamic physical process, and is powerful to express complex relationship between entities. In order to simulate the group behavior and real-time fire effect, we incorporate tenability analysis into the CA model in a dynamical fire

environment. Based on CA model, the proposed model is implemented and verified by a numerical example.

## 2.2 The Basic Framework of Fire Evacuation

When the fire breaks out in high-rise buildings, the pedestrian evacuation time from the top to the floor is increasing substantially. Owing to larger number of people inside, it is easy to make the main evacuation channels congestion [23]. At the same time, high-rise building fire behaviour and smoke spread upward quickly, which has a greater threat to the safety and health of the crowd? Because building layout is more complex, people who are not familiar with the environment cannot distinguish the direction around a fire smoke spread. It is difficult to find suitable evacuation route. In the evacuation process, building layout, fire development and other's behavior can impact individual selection of evacuation route.

To sum up, personnel evacuation model is a behaviour simulation of the special group in a specific environment and specific places, under different fire developmental stage[24]. Therefore, individual and group behaviour in an evacuation process, the construction of the building, and fire development all has significant influence. As a consequence, we make up the basic framework model. Figure1 displays the basic framework and the process of evacuation model. Specifically, we give some descriptions of the elements of the model in detail:

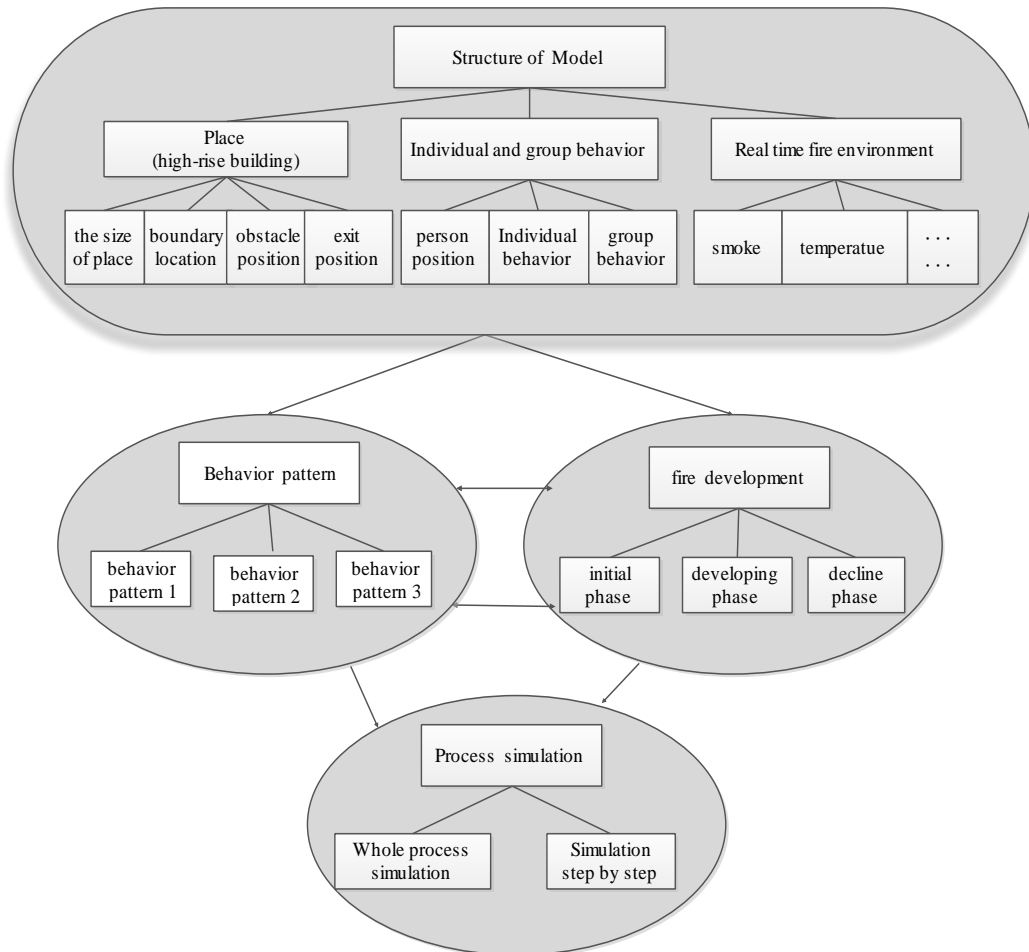


Figure 1. Structure of Model

Places and building structure: including building size, spatial layout, position, how many floors, the position and size of obstacle, boundary location, exit location and size etc.

Individual and group behavior: including the number of people need to evacuate, individual location, individual characteristics (young or old or disabled), Individual competitiveness and following behavior etc.

Real time fire environment: including smoke and temperature, CO, CO<sub>2</sub>, different fire developmental stage, the number and location of the fire etc.

In this paper, we combine behavior pattern (group behavior) and real time fire development level together to better show us the evacuation situation when a emergency fire occurs in the high-rise building. With the different stage of fire spread, the fire status has large impact on the individual and group evacuation behavior, which is ignored in the previous research works. The model uses the motor schema of an intelligent mobile robot and considers the effects of the fire environment on evacuation behavior, i.e. the physiological and psychological effects of the fire which result in low-efficiency behavior. Because of the temperature and smoke, reduced oxygen, increased carbon dioxide and carbon monoxide; it will affect the evacuation route and evacuation speed. Meanwhile, people who is not clear on the house or weakness, will be competing with and rely on others to survive in the emergency. We consider occupant's individual character and following behavior. This article focuses on analyzing the influence of the following movement on the pedestrian behavior and evacuation time in some cases. Hence, as for group behavior and real time fire situation, they connect and influence each other too, leading to the larger difficult to evacuate away from the high-rise building.

### 2.3 The Pedestrian Evacuation Group Behavior Model

Firstly, the article gives out the following set of simulation environment elements; at the same time, individuality and behavior characters to facilitate the construction of the model was represented. Then following model was proposed with considering individual behavior and group in the course of fire, the concrete computation methods are described in detail.

#### (1) Condition setting

Grid partition: uniform grid division of the building space, each grid coincides with a cell. Built on intensive flow in typical personnel allocation standard, each cell shall be corresponding to 0.5m\*0.5m space.

Grid attribute: as showed in Figure 2, each grid may be occupied by walls, obstacles, or the evacuees, may also be exits, or is empty. The scene can be utilized next time directly.

Personnel characteristics: only thinking body strong degree of each person, dividing into two kinds(Figure 2), such as strong (young) and weak (Old or children or disability). The position, number, density and characteristics of evacuation can be randomly generated, can be preset depending upon the actual situation.

Time step: the rule is that all the personal positions are changing synchronously, at each time step; each person can only move one grid. Then, according to well-known standard (the normal human walking speed is 1m /s), and each cell step time should be 0.5s.

Moving direction: Model using Moore type neighbourhood, evacuee has 8 possible directions of movement (Figure 3), each direction has different weight.

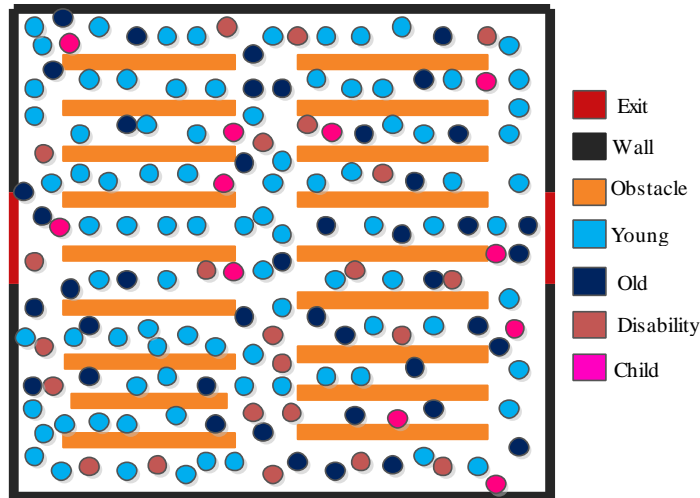


Figure 2. Attribute of Grid and Evacuees Characters

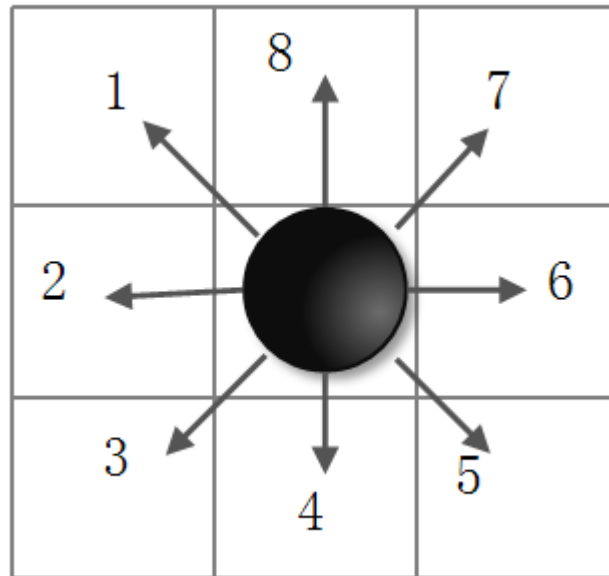


Figure 3.

Moving Direction

Possible

(2) Compute grid attractive probability

In this paper, to the best of my knowledge, we firstly present grid attractive probability parameters, and as a basis for individual choice of evacuation route. We assume that: When we calculate grid attractive probability according to each grid location, person will choose their maximum probability grid in their grid neighbourhood as the next step of moving target. Attractive probability of grid  $N(i, j)$  can be representation as  $P(i, j)$ :

$$P(i, j) = a_{ij} \cdot (k_{dis} P_{dis(i,j)} + k_{dir} P_{dir(i,j)}) \quad (2)$$

$P_{dis(i,j)}$  is said grid location attractive probability,  $k_{dis}$  is the influence coefficient of location attraction,  $P_{dir(i,j)}$  is grid direction attractive probability,  $k_{dir}$  is the influence coefficient of direction attractive.  $a_{ij}$  is adjustment coefficient of  $P(i,j)$  depended by grid property. When the grid is empty, we are given  $a_{ij} = 1$ , said  $N(i,j)$  grid can be used, vice versa. Given the exit condition only, location attraction probability  $P_{dis(i,j)}$  is based on the distances between grid to exit.

$$P_{dis(i,j)} = \frac{\max(D_{(i,j)}) - D_{(i,j)}}{\max(D_{(i,j)}) - \min(D_{(i,j)})} \quad (3)$$

In which  $D_{(i,j)} = \sqrt{(i_k - i)^2 + (j_k - j)^2}$  is the distances from grid  $N(i,j)$  to exit  $(i_k, j_k)$ . The shorter the grid distances near exit, the greater the location attraction probability.

We propose direction attractive probability to consider the effect of the following behavior in the evacuation process, so that the evacuation model is closer to reality. The basic assumption is that there are 8 possible directions of movement. Direction attractive probability in a certain view range can be obtained by the formula:

$$P_{dir(i,j)} = \frac{N_{dir(k)}}{\sum_{k=1}^{\delta} N_{dir(k)}} \quad (4)$$

$N_{dir(k)}$  is the total number of people moving to K direction in a field of view,  $k = (1, 2, \dots, 8)$ .

### (3) individual competition ability

Individual competition ability to solve conflict problem, when there are many people competing for the same grid in the simulation process. However, due to different individual features and survive capacity, people will compete with each other to firstly evacuate away, and person in different ages and body conditions own different individual competition ability. In the article, we define that Individual competition ability of E is given by Formula (5) which reflects the actual capacity in the evacuation process. It is defined according to the body strength properties of person A and the distance D to target grid D:

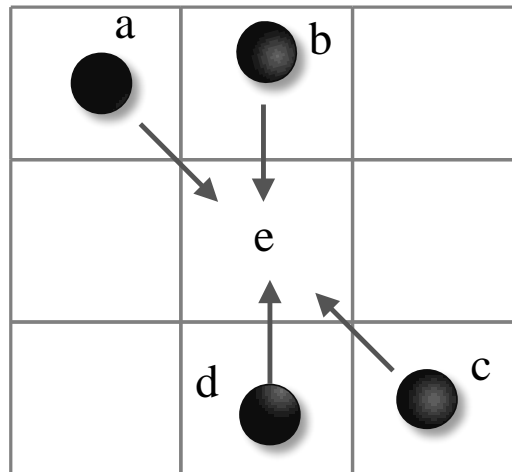
$$E = \frac{A}{D} \quad (5)$$

When the evacuation is young, we give  $A = \sqrt{2}$ , and when the evacuation is old or disabled,  $A=1$ . When the target grid is in up, down, left and right direction, set the  $D= 1$ , and when the target grid is in the diagonal direction, given  $D = \sqrt{2}$ . D is the distance to target grid when the target grid is in different direction as show in Fig.3, the distance is different when the direction of motion is different in the grids. Hence, as shown in Fig.4, the people located in grid a,b,c,d are young, disabled, old and young

Separately. And they compete with each other to arrive to the target grid e, according to the equation (5) we can get the individual competition ability of the four people which are

$$E_a = \frac{\sqrt{2}}{\sqrt{2}} = 1, E_b = \frac{1}{1} = 1, E_c = \frac{1}{\sqrt{2}} = \frac{\sqrt{2}}{2}, E_d = \frac{\sqrt{2}}{1} = \sqrt{2}$$

Respectively. Individual competition ability will prolong evacuation time compared with minimum distance movement And only in particular conditions that guides exist, the following illustration show beneficial to the evacuation process.



**Figure 4. Competition Capability**

#### 2.4 Real Time Fire Environment Model

As we know, fire is developing fast and its distribution is different. Fire behavior and smoke strength have a great effect on group behavior, especially influencing people's judgment and health. Therefore, we use FDS to, which is a fire simulation software developed by USA, simulate the development of fire in high-rise building, namely the smoke concentration, temperature in the building, O<sub>2</sub>, CO and CO<sub>2</sub> which is in different space-time distribution. And the simulation results are input into the evacuation model.

In the evacuation process, the staff is deemed as the intelligent mobile robot, in real environment, personnel movement patterns may include goal-directed behavior (move to the exit), obstacle avoidance behavior (avoid the obstacles) and bypass behavior (bypass the obstacles), and goal-directed behaviors show us the attraction of the target (export) to person, let C and Q be the radius of the control region and dead zone, d is the distance between person and the obstacle. And the computation rule is as following:

$$|S_{mo}| = \begin{cases} 1, d \geq C; \\ \frac{d-Q}{C-Q}, Q \leq d < C; \\ \infty, d < Q \end{cases} \quad (6)$$

The direction of goal-directed behavior is along line between the person and the target center, towards the target direction.

When people encounter obstacles or other personnel, they will escape and try to bypass them. Avoidance behaviour reflects the repulsion of obstacle on person, let S be the radius of influence, and the obstacle beyond the radius of influence does not have impact on people. In response, M is the security boundary. And the calculation rules are as follows:

$$|S_{av}| = |S_{sw}| = \begin{cases} 0, d \geq S; \\ \frac{S-d}{S-M}, M \leq d < S; \\ \infty, d < M \end{cases} \quad (7)$$

The direction of obstacle avoidance behavior is along the line between the center of barriers and the personnel, towards the direction far away from the obstacles. The amplitude value of bypass behavior is the same to the obstacle avoidance behavior, namely:  $|S_{av}| = |S_{sw}|$ . And the direction of bypass behavior is perpendicular to the line between the centre of barriers and the people, obviously it has 2 directions, the model of this paper only chooses one randomly. The motion patterns are independent of each other, and need to make parallel processing.

The physiological effects of fire on evacuation behaviour of a person will change people behavior. With respect to the walls, tables and chairs and other real obstacles, person in a fire environment will increase 2 basic behavior namely: avoid virtual obstacle behavior of  $S_{susv}$  which means that people do not happen to the obstacle from the beginning and avoid it in the evacuation path, and bypass the virtual obstacle behaviour of  $S_{susw}$  which means that people will happen to the obstacle in the process and try his best to bypass the obstacle. The obvious difference between  $S_{susv}$  and  $S_{susw}$  is that  $S_{ne} |S_{ne}| = 12\lambda$  denotes different value of random direction. Let  $T$  and  $\xi_s$  respectively are gas temperature and concentration at the height of  $Z = 1.7m$ . Subscript  $0$  and  $cr$  is the initial value and the critical value of death,  $a1, a2$  is a constant, the calculation rules:

$$|S_{susv}| = |S_{susw}| = \begin{cases} 0, d \geq S; \\ \frac{S-d}{S-M} \left( a_1 \frac{T-T_0}{T_{cr}-T_0} + a_2 \frac{\xi_0}{\xi_{cr}} \right), M \leq d < S; S_{ne} |S_{ne}| = 12\lambda \\ \infty, d < M \end{cases} \quad (8)$$

The direction of virtual obstacle avoidance behaviour is along the line between the centre of virtual barriers and the person, towards the direction far away from the virtual obstacles. The amplitude value of bypass behaviour is the same to the virtual obstacle avoidance behaviour. And the direction of bypass behaviour is perpendicular to the line between the centre of virtual barriers and the people, obviously it has 2 directions, the model of this paper only chooses one randomly.

Under fire, people become nervous, may not make a correct judgment of its environment. Thus cause personnel evacuation direction of dislocation, reflect the influence of fire on personnel psychology. As considerable nervous behaviour, operational rules are as follows:

$$|S_{ne}| = 1 \quad (9)$$

Nervous behaviour direction is a pseudo random direction between  $rad\ 0$  and  $2\pi\ rad$ .

### 3. Simulation Experiment

Software and hardware environment of simulation experiment: they are in the same laboratory including common software and hardware environment, namely CPU Intel core 4.0GHz, memory for the DDRII4G, operating system is Windows7.0 professional edition, and we use FDS and CA model to implement our simulation.

We apply the evacuation model of CA aforementioned effectively, and construct a high-rise building whose layout is very multifaceted. The area of the scene is 30m\*30m we achieve our evacuation behaviour and real time fire simulation in this virtual



environment. Moreover, grid partition rules in accordance with the aforementioned each cell corresponds to 0.5m\*0.5m space, we first divide the virtual scene into 60\*60 grids. The fire scenario and smoke level are emulated by FDS. Coupled with the building deformation data derived from the structural analysis, the integrated process of evacuation is described in a assigned scene. The health and mobility status is deemed to be normal when occupants are generated. The number of people is 300 in a virtual scene of the evacuation. Reaction time is assumed as 15s for the occupants near fire, 25s for others,  $k_{dis}=0.8$ ,  $k_{dir}=0.2$ ,  $a_{ij}=0.05$ .

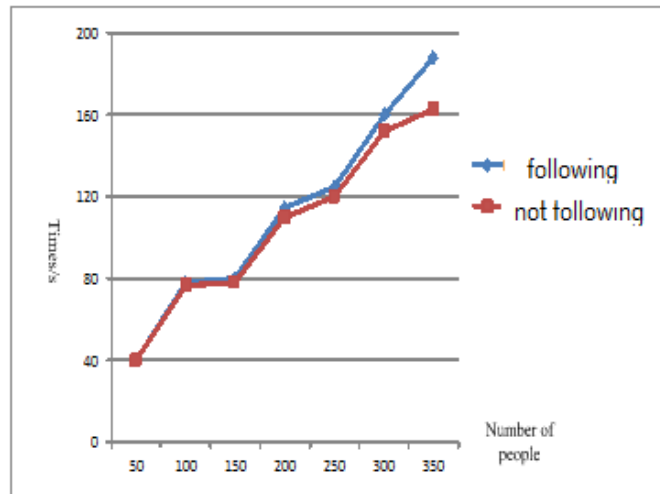
(1) experiment 1 considering group behavior

If individual moves and arrive to exports, we reckon as evacuation is successful, and the statistical time step can be computed. Therefore, the total evacuation time is the ultimate evacuation successful time in the virtual scene. In this paper, we simulate for 10 times, and then compute average total evacuation time needed in the behaviour mode 1 (that is, without taking into account the following behavior) and behaviour mode 2 (consider following behaviour), respectively 164s and 183s. We can see that the time in the following behaviour patterns is more than not following behaviour. Also, Table1 shows us that at the same time step, the number of evacuation people in following is less than the general behavior mode

**Table1. Number of Un-evacuated Occupants in Same Time Step between Two Behaviour Modes**

Time step	Number of people un-evacuated (Not following behaviour)	Number of people un-evacuated (following behaviour)
0	300	300
40	226	225
60	143	158
80	84	90
120	30	42
160	5	17

At the same time, we discover that with the increasing of the number of person evacuation, following behaviour has large impact on evacuation time. Experiments are performed on two kinds of behaviour patterns, the number of person from 30 to 300. The simulation results are presented in figure 5. As we can see from the graph, when the evacuation of person is less (such as less than 100 people), two kinds of behaviour pattern of results is consistent or similar, namely not have the following conditions, the individual is mainly based on their own judgment to select the nearest evacuation. With the increase of the number of person, following behavior can cause interference on the behaviour of the evacuation of persons under certain conditions, so that the whole evacuation process is delayed



**Figure 5. Evacuation Time Curves with Different Number of People**

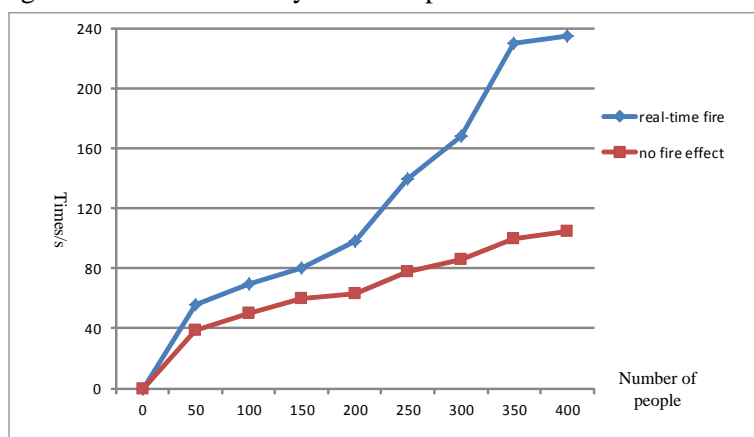
(2) experiment 2 considering real time fire effect

Now, we consider how to real time fire effect on evacuation time and personal behaviour . Table 2 is a consequence comparison between no fire effect and real time fire environment, when the same initial conditions, the number of persons and the initial position, the total evacuation time was extended by 47s, considering the influence of the fire environment.

**Table2. Comparison Analysis of Two Different Scenarios**

Scenario	Number of people evacuated	evacuation time	activity index
No fire effect	300	156	1.0
Real time fire	300	203	0.84

Activity index for motion measure of person, under normal circumstances, the value is 1. The simulation results demonstrate that, the average activity index of person is 0.83 under real time fire. What dropping of the index show us is that the walking speed of the passenger is reduced, the evacuation movement is limited, and fire environment has great influence through calculation and analysis on the pedestrian evacuation.



**Figure 6. Evacuation Time Curves**

Meanwhile, we discover that real time fire has large impact on evacuation time, with the increasing of the number of person. Experiments are performed on two kinds of Scenarios, the number of person from 50 to 300. The simulation results are illustrated in figure 6. As we can see from the graph, when the evacuation of persons is less (such as less than 50 people), the results both are similar. However, with the increase of the number of person, fire development can make the entire evacuation process delayed.

#### 4. Conclusion

Evacuation of persons in case of emergency is very complex, it will be affected by the environment, the individual psychological quality and physical quality, real time fire and so on. In this study, firstly, we build a entire fire evacuation framework and the process of evacuation mode, which contains places and building structure, individual and group behavior and real time fire environment. Secondly, a model based on cellular automata is designed to research the group and fire spread effect on evacuation. We consider group behaviour and define individual competition ability. Person will be following others who have strong importance. Simultaneously, we also take real time fire progress into account in the evacuation simulation. Finally, we apply the evacuation model of CA aforementioned and implement simulation experiments. The simulation results demonstrate both group behaviour and real time in the fire have great influence on the pedestrian evacuation, delaying the evacuation time. Additionally, the proposed model can also be utilized as a tool to investigate the effect of guiders through case study. The factors to consider in this study can't be all covered, that is to say, the evacuation model now established as a starting point, there are many issues and details need to be more in-depth study and discussion. Due to the difficult of getting the real data of fire emergency, we just simulate the evacuation process to compare the different experiments. In the future, we will further deeply collect the actual fire data in different area from the government to prove the effect of our model considering both group behavior and real time fire.

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