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Simulation of a pediatric hospital in evacuation considering groups

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ABSTRACT

Pedestrians will form groups in both normal and emergency sometimes. Members of these groups usually have certain social relations. We study emergency evacuation of pedestrians in a pediatric hospital in this paper. Pedestrians there have their own particularities. First of all, all patients are children. Secondly, the patients usually have no ability to see a doctor alone. They are always accompanied by their families. Thirdly, children of different ages move at different speeds, which is heterogeneous. Fourthly, pedestrians usually move in family units. Family units and independent pedestrians are also heterogeneous. According to our actual observations, pedestrians are mostly composed of three-person groups, two-person groups and independent ones. Each group usually has one leader and the rest are followers. We use an extended cellular automata model considering groups to study such evacuation. The rule of both overlapping and speeding up are set in the model to realize the change from heterogeneous to homogeneous from the view of speed. The local density field and its range R are introduced. The field can lead pedestrians move to the area with low density. The range R = 4 is optimal because of the family relation. The priority order is added to avoid conflicts. Groups with child have priority over independent pedestrians. The cohesive distance between leader and follower ensures members of the group always stay together, but the shape of the group is changeable in simulations. The evacuation time, waiting time and path of each pedestrian are analyzed. The simulation verifies the phenomenon that pedestrians behind tend to follow the front. The rules together release more free space to drastically reduce evacuation time and waiting time of groups, but independent pedestrians are not influenced greatly.

1. Introduction

Research on crowded people mainly focuses on public places such as subway stations [1,2], shopping malls [3,4] and schools [5]. Hospitals are also typical crowded public place in China, especially pediatric hospitals. There are more than 15 million newborns every year according to statistics. The number of children aged 0 to 14 years is about 230 million. The proportion of sick children in the total sick population in China has increased gradually in recent years [6]. The number of pediatricians per thousand children only reaches 0.69 from the perspective of resource allocation. It is still lagging behind the allocation standard of 0.85 ~ 1.30 pediatricians per thousand population in developed countries such as the United States, Canada and Japan [7]. As a result, pediatric hospitals are always overwhelmed. Major medical resources are concentrated in big cities in China, such as Beijing and Shanghai. Sick children in these pediatric hospitals not only come from this city due to the high medical standards and advanced medical facilities, but also from the surrounding ones. A Grade III Level A pediatric hospital in Shanghai receives more than 5000 outpatient visits every day [8,9].

Evacuees are heterogeneous in pediatric hospitals. Not only are there differences in behavior and speed between adults and

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children, but also between individuals and families. The family groups have some special characteristics. Firstly, all patients are children and they have no independent ability to see a doctor. Sick children are accompanied by their family members when they go to the hospital. Secondly, family move as a unit during medical treatment. They will eventually reunite even if there is a brief separation. For example, parents leave to get the medicine. Thirdly, children under age 4 are usually cradled by their parent. Cradling these children will not greatly affect the speed of the parent because of their low weight. Fourthly, children aged 4 to 8 years are led by their parents. The speed of the whole family group with child aged 4 to 8 years is relatively slow because the parents need to match themselves with their child. For example, there will be waiting or even backtracking to ensure that the children will not be separated. The cohesiveness of the group is very strong. Finally, each family group actually tends to hold one member as the leader, such as the father, while others are followers.

There are some studies about homogeneous evacuees considering groups. It can be observed that pedestrians will form groups in both normal and emergency [10-12]. Data on celebrating a football victory indicated that the majority of participants were with one or more friends. In other words, they were in groups. The phenomenon of group-level was paid more attention to the conceptualization of crowd behavior [10]. Mehdi Moussaïd et al. [11] analyzed the movement of approximately 1500 pedestrian groups under natural condition. The social interactions among group members generated typical group walking patterns that influenced crowd dynamics. Group members tended to walk side by side. They would form a line perpendicular to the walking direction at low density. The linear walking formation bent forward and formed a V-shape when the density was high. Bonneaud et al. [12] introduced a study of small crowds walking towards a common goal. It was proposed to make the link between individual behavior and crowd dynamics. Participants formed a cohesive group and did not merely treat one another as obstacles. The phenomenon of the kin behavior often occurred during evacuation. The model presented by Yang et al. [13] was applied to simulate the evacuation with respect to the kin behavior. Many interesting phenomena during real evacuation, such as incoherence, jamming, gathering, backtracking and waiting, were simulated. It was found preliminarily that the proper kin behavior was beneficial to improve the evacuation efficiency. Li-Li et al. [14] proposed an extended floor field CA model to describe the walking behavior of pedestrian groups. The model represented the movement of pedestrian groups realistically. The walking behavior of groups had an important impact on the dynamics of pedestrian flow. It had some negative effects, especially when the group density was high. Large groups (such as tourists or hiking groups) would split up typically [11]. Group members only thought about pedestrians around them when they were too far apart to communicate. Therefore, clusters of 2 to 4 people would appear within the group.

Some scholars have also studied the evacuation of heterogeneous evacuees considering groups. Heterogeneity was reflected in speed difference or group sizes. You et al. [15] proposed a novel methodology for calculating movement profit based on CA model. Small groups had six different forms in terms of size. The simulation results showed that the evacuation efficiency of different forms of small groups was very different. The work of Lu et al. [16] was calibrated with a few field experiments of crowd evacuation conducted in a university building. The floor field CA model was based on the leader-follower behavioral rule. The crowds in field experiments were heterogeneous. Both group sizes and the speeds were different. The total crowd evacuation time increased significantly with the presence of pedestrian groups in the crowd. The model presented by Crociani et al. [17] could improve not only the ability to generate overall aggregated dynamics, but also the precision in the microscopic group dynamics. It paid attention to the shape of two-person groups. Ma et al. [18] studied the crowd dynamic on different social relations and the impacts of small groups in emergency evacuation. Three experiments were conducted in an 11-story office building. Different types of pedestrians had different behaviors and speeds in the experiments. Small group behavior had a positive effect on crowd dynamics when evacuees understood and cooperated with one another. Conversely, there were negative effects. The work of Drury et al. [19] opened the way for considering the principles of SCT as an alternative explanatory framework. The social identity framework had been able to provide explanations of small group processes and group productivity. The emphasis on social bonds rightly stressed the prevalence of solidaristic behavior.

Overlapping often occurs in groups, especially in emergency evacuation. Crociani et al. [17] described the mechanism of overlapping. The model allowed two pedestrians to temporarily occupy the same cell at the same step in high density case. Overlapping was allowed only in the case of counter-flow situations. In order to model the spatial behavior of pedestrian movement, both simple and structured groups were mentioned. Overlapping between agents of the same group was not allowed in simulations. Bandini et al. [20] proposed an extended CA model based on agent. The model allowed pedestrians to overlap transiently with a small probability. Two pedestrians (a maximum of) were allowed to stay in the same cell at each step. The rationale was the fact that pedestrians tended to rotate their bodies to pass in tight spaces, especially in high densities.

Some scholars have conducted experiments to study the evacuation behavior of groups. James [21] analyzed group data in a field project. The distribution of different sizes of group was fitted with Poisson model. The relationships governing the combinations of individuals were relatively stable. Zhang et al. [22] studied the evacuation of students in a classroom. Some typical characteristics of evacuation, such as variable speed and formation of groups, were found by studying the video record. Haghani et al. [23] performed experiments with various group sizes. Group size had a significant impact on pre-action and decision time. Subjects showed a behavior opposite to herding in making exit decisions, which was similar with that of individuals. In order to investigate the impact of social groups on evacuations, Cornelia von Krüchten et al. [24] performed an empirical study with pupils. Several evacuations with groups of different sizes and different interactions were carried out. The analysis showed that evacuation time for large groups might decrease due to self-ordering effects. Social groups were approximated as ellipses oriented along their moving direction.

The pedestrian groups were all composed of healthy people in most studies. The members within those groups were regarded as homogeneous whether they are friends or family members. The crowd is obviously heterogeneous in pediatric hospitals. Both behaviors and speeds of different types of pedestrians are different. The evacuees consist of many family groups. Family groups contains sick children. Some of the children such as ones under age 4 are always be cradled by the adults. Some of the children such as ones aged 4 to 8 years move slowly in normal. However, they will be cradled in arms in emergency. Thus overlapping occurs during the evacuation. This study focuses on the evacuation of family groups with sick children. All independent pedestrians are simply assumed to walk at the same speed. Parents with cradled younger children can struggle to reach the same speed as independent pedestrians in emergency. Older children over age 8 can also reach the speed of independent pedestrians with the urging force of parents. When overlapping occurs, the speed of the group will change. The whole will change from heterogeneous to homogeneous from the aspect of speed.

The rest of this paper is organized as follows. The second section introduces the model and transition probability. The third section introduces the rules. Case study and analysis of simulation results are performed in Section 4. The last section gives conclusion and suggestions for future works.

2. Model

2.1. Basic model

In this study, an extended CA model that considers groups is established to simulate the evacuation of a pediatric hospital. The model is built on a two-dimensional space, which is divided into square grids. The cell size is 0.5 m × 0.5 m [25].

Most of the pedestrians move in family groups through our practical observations in a pediatric hospital. These pedestrians include three-person groups, two-person groups and independent ones. G-2 and G-3 refer to the two-person group and the three-person one, respectively. Each group has at least one child and one adult. A G-3 is made up of parents and an accompanied child. A G-2 is made up of one of parents and an accompanied child generally. As the percentage of four-person groups or larger ones is very small, it is not considered in this paper. It is impossible for a little sick child to go to the hospital alone, so independent pedestrians are generally adults. Independent pedestrians include medical staff and parent who leaves the group shortly to complete a certain task alone. The group will not be separated since one member of the group is a sick child. The cohesion of the group is very strong. Each group usually has one leader, and the rest are the followers. The male always acts as the leader.

Moore neighborhood is adopted in the model. Each pedestrian can move to the adjacent cell or remain stationary at each time step, as shown in the Fig. 1.

2.2. Transition probability

The movement probability of each pedestrian is calculated as follows.

For leader or independent pedestrian

$$P_{i,j}^{L} = N\exp(-k_S S_{i,j})\exp(k_D D_{i,j})exp(-k_A E_{i,j})(1-\eta_{i,j})\varepsilon_{i,j} \tag{1}$$

For other group members

$$P_{i,j}^{F} = N\exp(-k_S S_{i,j})\exp(k_D D_{i,j})exp(-k_A E_{i,j})\exp(-k_d d_{l,m})(1-\eta_{i,j})\varepsilon_{i,j} \tag{2}$$

Where,

$$\eta_{i,j}=\begin{cases} 0, & \textit{if the cell}(i,j)\textit{ is empty } (3) \\ 1, & \textit{if the cell}(i,j)\textit{ is occupied by a pedestrian } (4) \end{cases}$$

$$\varepsilon_{i,j}=\begin{cases} 0, & \textit{if the cell}(i,j)\textit{ is occupied by an obstacle } (5) \\ 1, & \textit{if the cell}(i,j)\textit{ is empty } (6) \end{cases}$$

N is the normalization;

For leader or independent pedestrian,

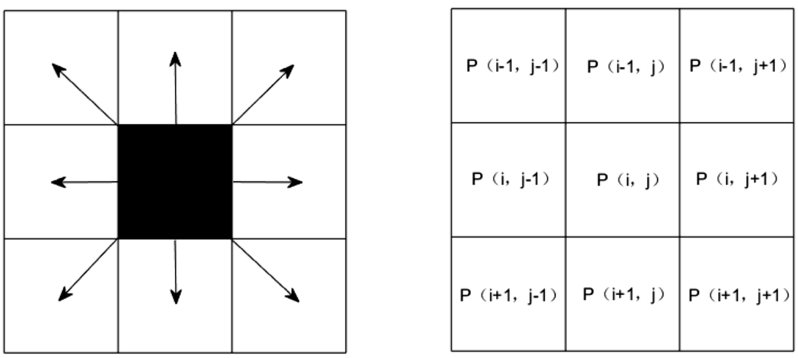

Fig. 1. Moore neighborhood.

$$N = [\sum \exp(-k_S S_{i,j})\exp(k_D D_{i,j})exp(-k_A E_{i,j})(1-\eta_{i,j})\varepsilon_{i,j}\ ]^{-1} \tag{7}$$

For other group members,

$$N = [\sum \exp(-k_S S_{i,j})\exp(k_D D_{i,j})\exp(-k_A E_{i,j})\exp(-k_d d_{l,m})(1-\eta_{i,j})\varepsilon_{i,j}\ ]^{-1} \tag{8}$$

k_S is the sensitivity parameter that determines the weight of the static field $S_{i,j}$;

k_D is the sensitivity parameter that determines the weight of the dynamic field $D_{i,j}$;

k_A is the sensitivity parameter of local density field;

k_d is the dependence of follower on the leader that is related to the cohesive distance from the follower to the leader;

$S_{i,j}$ is static field that is expressed by Euclidean distance from the exit. It is set to the shortest distance from the exit. Ψ represents the set of cells occupied by the exit. For cell (i, j),

$$S_{i,j} = \min_{(i_x, j_y)\in\Psi} \sqrt{(i-i_x)^2 + (j-j_y)^2} \tag{9}$$

$D_{i,j}$ is dynamic field. The calculation method is referred to [27];

$E_{i,j}$ is local density field that describes the crowding degree of the surrounding environment;

$d_{l,m}$ is the cohesive distance between follower and leader, $(i_l,\ j_l)$ is the coordinate of the leader corresponding to the follower, $(i_m,\ j_m)$ is the coordinate of follower. The calculation of $d_{l,m}$ is Eq. (10).

$$d_{l,m}(i,j) = \sqrt{(i_l - i_m)^2 + (j_l - j_m)^2} \tag{10}$$

The probability $P_{i,j}^F$ of the follower moving to the cell occupied by the leader reaches the maximum when $d_{l,m}$ is 0. The farther the cell is from the leader, the less probability it is, as shown in Fig. 2. In other words, the closer the cell is to the leader, the greater the probability that the follower will move towards it.

The model uses static field $S_{i,j}$ to describe the behavior to find the shortest path in the process of evacuation. A static field does not change over time. The dynamic field $D_{i,j}$ records the virtual track of pedestrians and describes the behavior of pedestrians following their predecessors during evacuation. The dynamic field diffuses and decays with time. $E_{i,j}$ is local density field, which describes the crowding degree of the surrounding environment. The parameter values are described in Section 4.3.

In traditional CA model [26], the calculation of transition probability only considers dynamic field $D_{i,j}$ and static field $S_{i,j}$. The calculation formula is Eq. (11).

$$P_{i,j} = N\exp(-k_S S_{i,j})\exp(k_D D_{i,j})(1-\eta_{i,j})\varepsilon_{i,j} \tag{11}$$

The local density field is introduced in our model, as shown in Eq. (1). The field $E_{i,j}$ can lead pedestrians to move to the area with low density. The value of $E_{i,j}$ is increased by 1 within a certain range when one cell around the object cell is occupied by a pedestrian (including the object cell). The initial value of $E_{i,j}$ is 0. The calculation formula is Eq. (12). In Fig. 3, the gray box is the calculation range of local density field when $R = 4$.

$$E_{i_0 j_0} = \sum \delta_{mn}(m \in [i_0 - R,\ i_0 + R],\ n \in [j_0 - R,\ j_0 + R]) \tag{12}$$

Where,

(i_o, j_o) is the object cell;

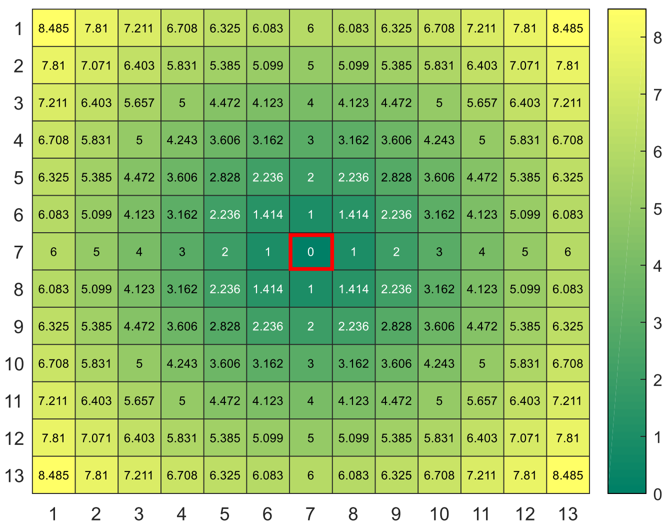

Fig. 2. The cohesive distance between follower and leader.

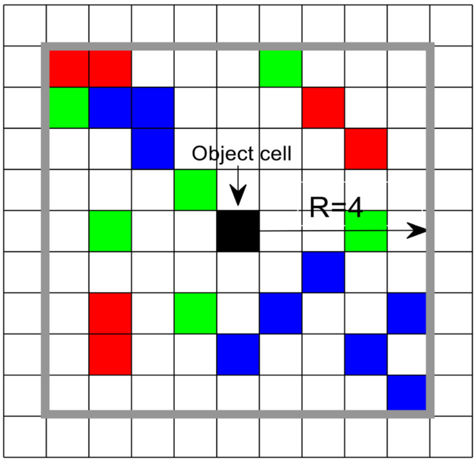

Fig. 3. Local density field.

δ_{mn} indicates whether the cell (m, n) is occupied by a pedestrian.

$$\delta_{mn}=\begin{cases} 1, \ if \ \ the \ cell(m, \ n) \ is \ occupied \ by \ a \ pedestrian \\ 0, \ if \ \ the \ cell(m, \ n) is \ not \ occupied \ by \ a \ pedestrian \end{cases} \tag{13}$$

The Leader-follower rule refers to [16].The cohesive distance $d_{l,m}$ between leader and follower is also considered as shown in Eq. (2). It leads followers to always move close to their leader. The shape of groups is changeable, as shown in Fig. 4.

2.3. Priority order

Pedestrians move with sequential update rules. There is one child patient in each group, so the position of the group members is updated prior to independent pedestrians.

All pedestrians update their position in order. The order of update rule here is: leaders in a G-3 or G-2→ followers in a G-3 or G-2→ independent pedestrians. For a group, the position of the leader is updated first. Then the position of one of the followers is updated, as shown in Figs. 5 and 6. The exit is located below.

3. Rules

This paper studies the mechanism of overlapping. Overlapping here means that parents cradle children aged 4 to 8 years because of their low height and light weight in emergency. Groups with children move slowly, but they will speed up during an emergency evacuation. Groups change from heterogeneous to homogeneous by speeding up. The way to achieve the simulations is to add both overlapping and speeding rules.

3.1. Overlapping rule

The model allows pedestrians to overlap when certain conditions are met. According to the research conducted by Jin et al. [28] based on the social force model, pedestrians are in free flow when the density is $0\sim2.3\ ped/m^2$. Pedestrians belongs to congested flow when the density is $2.3\sim6\ ped/m^2$. It is over-congested flow when the density is $6\sim8\ ped/m^2$. People usually do not want to exceed $6\ ped/m^2$in their daily lives because they will feel very uncomfortable. The visual fields of children are limited due to their height. They will feel anxious and panic when many adults walk around them.

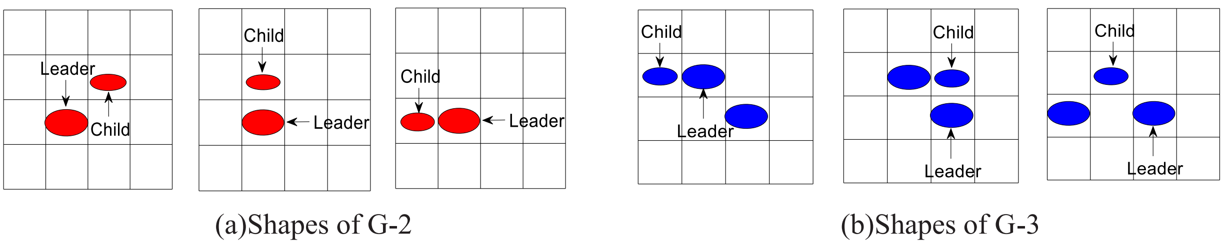

Fig. 4. Different shapes considering the cohesive distance.

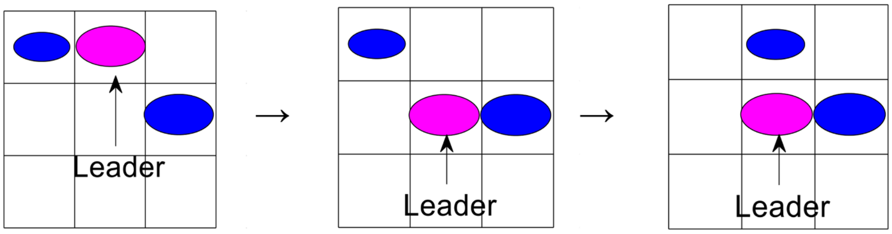

Fig. 5. Position update for a G-3.

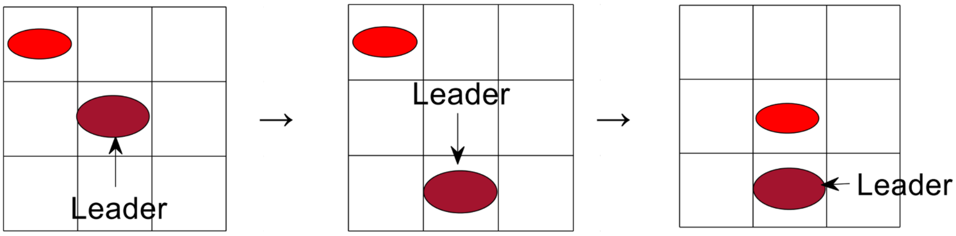

Fig. 6. Position update for a G-2.

Therefore, the model allows two special pedestrians to be in the same cell at the same time. It is the real. Two adults temporarily occupy the same cell at high density in some studies on overlapping, as shown in Fig. 7. The practical significance of overlapping is that pedestrians tend to rotate their bodies to pass a crowded section. Overlapping usually occurs in two-way traffic [17,20]. In this study, children aged 4 to 8 years are led by their parents in normal. These children will be cradled by their parent in emergency. A G-2 with child aged 4 to 8 years will occupy two cells in normal. However, the child in the group will be cradled in emergency. Thus, the adult and the accompanied child occupy the same cell in emergency, as shown in Fig. 8(a). A G-3 with child aged 4 to 8 years occupies three cells in normal, while it occupies two cells because an adult cradles the child in emergency, as shown in Fig. 8(b).

Walking parameters such as step frequency, speed and step length are all controlled by the maturation process until at approximately age 4, while the continuous changes after age 5 depend on the body height and limb length according to the study of Najmanova and Ronchi [30]. The sick children are weak in pediatric hospital. Their ability to walk is also limited by their physical condition. Therefore, sick children under age 4 are always cradled in arms by adults in pediatric hospital. According to both the data released by national health ministry of China in Table 1 and our actual observations, children aged 4 to 8 years are led by adults in normal. The weight and height of children aged 4 to 8 years are within the range that adults can cradle and the walking speed of adults is not affected greatly. So these children will be cradled in arms in emergency, namely the overlapping in simulations. Children over age 8 can walk by themselves but slower than adults in normal. They can catch up adults in the group in emergency. Children over age 8 will not be cradled.

The proportion of children of all ages is roughly shown in Table 2 according to our actual observations.

Figs. 9 and 10 show situations in which the leader of G-3 or G-2 cradle the child in arms, respectively.

3.2. Speeding up rule

Pedestrians are heterogeneous in normal. The speeds are shown in Table 3 [29,30]. The speed of groups depends on the slowest or the slower member in the group. The slowest or the slower member is usually child. The evacuees are homogeneous because all the pedestrians are assumed to have the same speed in emergency for simplification. The adults in the group will not allow the child walk slowly. Instead, they will cradle the child in arms to improve the speed of the group or urge the child speed up. It will improve the evacuation efficiency and be better to protect the child.

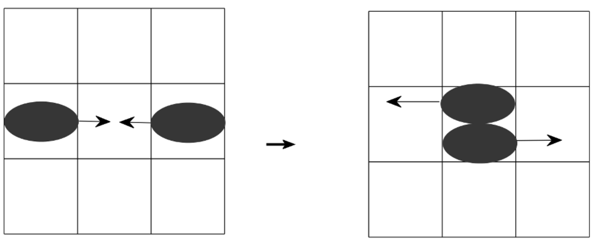

Fig. 7. Overlapping in bidirectional pedestrian flow in non-emergency situations.

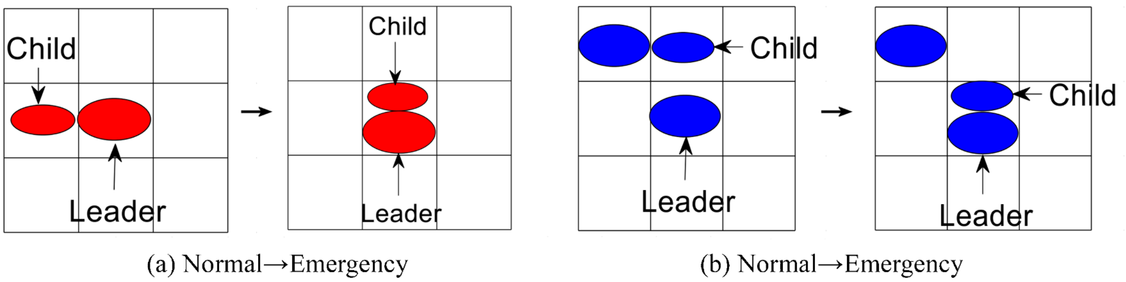

Fig. 8. Overlapping of an adult and an accompanied child.

Table 1
Height and weight of children(released by national health ministry of China).

Age	Male weight (kg)	Male height (cm)	Female weight (kg)	Female height (cm)
2.0	11.2–14.0	84.3–91.0	10.6–13.2	83.3–89.8
2.5	12.1–15.3	88.9–95.8	11.7–14.7	87.9–94.7
3.0	13.0–16.4	91.1–98.7	12.6–16.1	90.2–98.1
3.5	13.9–17.6	95.0–103.1	13.5–17.2	94.0–101.8
4.0	14.8–18.7	98.7–107.2	14.3–18.3	97.6–105.7
4.5	15.7–19.9	102.1–111.0	15.0–19.4	100.9–109.3
5.0	16.6–21.1	105.3–114.5	15.7–20.4	104.0–112.8
5.5	17.4–22.3	108.4–117.8	16.5–21.6	106.9–116.2
6.0	18.4–23.6	111.2–121.0	17.3–22.9	109.7–119.6
7.0	20.2–26.5	116.6–126.8	19.1–26.0	115.1–126.2
8.0	22.2–30.0	121.6–132.2	21.4–30.2	120.4–132.4
9.0	24.3–34.0	126.5–137.8	24.1–35.3	125.7–138.7
10.0	26.8–38.7	131.4–143.6	27.2–40.9	131.5–145.1

Table 2
The proportion of children of different ages.

Age	< 4	4 ~ 8	8 ~ 10	> 10
proportion	25%	40%	15%	20%

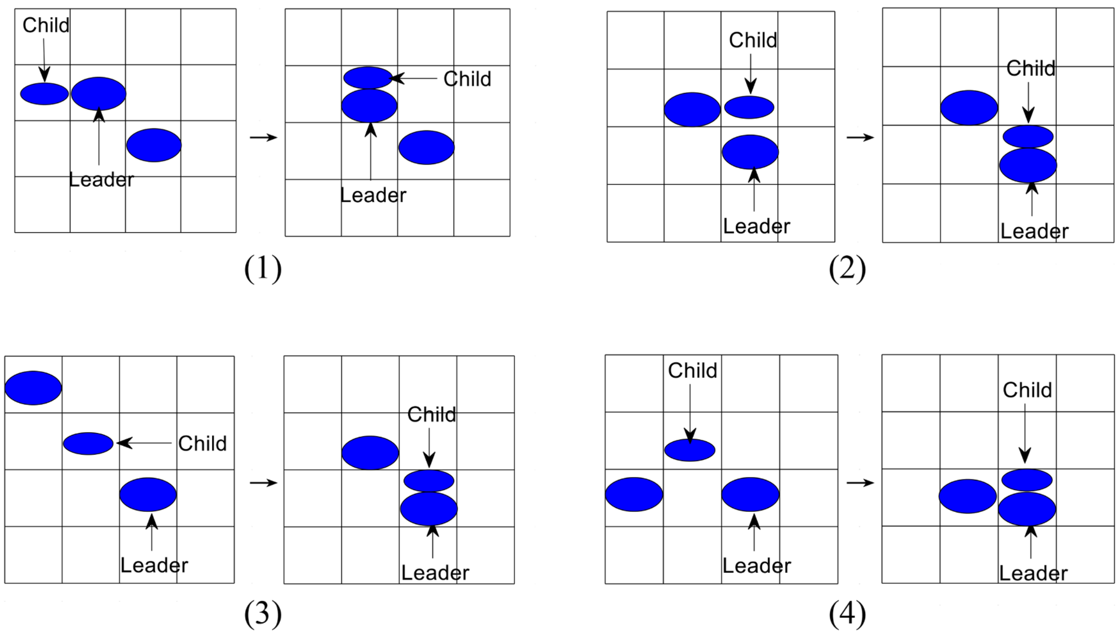

Fig. 9. Overlapping situations of G-3.

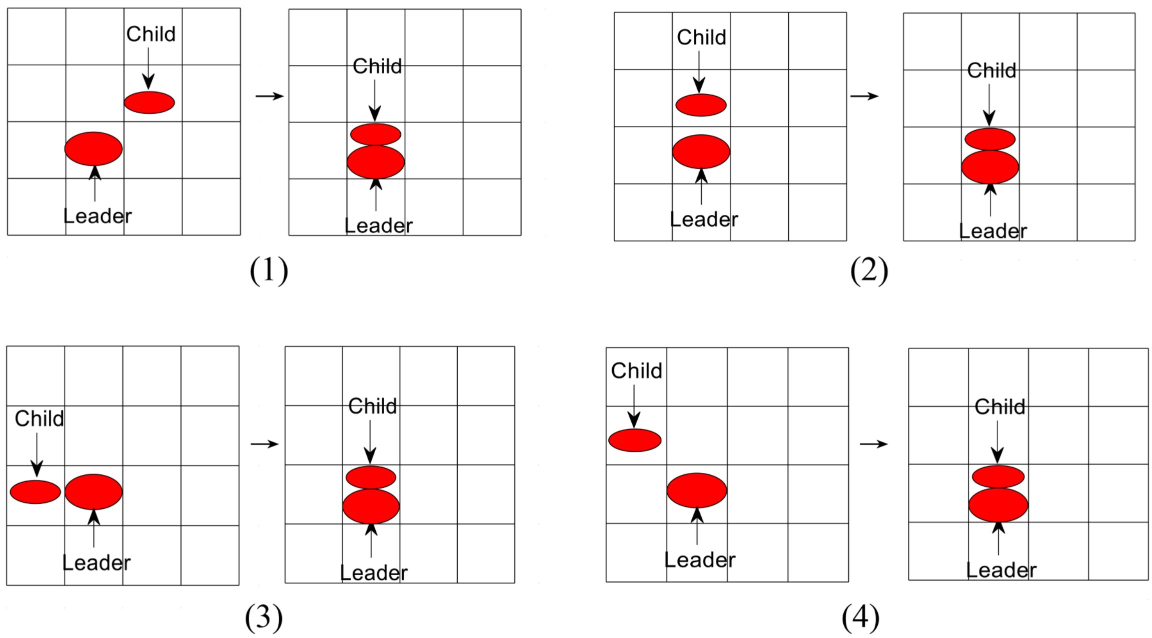

Fig. 10. Overlapping situations of G-2.

Table 3
Pedestrian movement speed.

	Normal(m/s)	Emergency(m/s)
Group with child under age 4	1.33	1.5
Group with child aged 4 ~ 8 years	1	1.5
Group with child over age 8	1.33	1.5
Independent pedestrians	1.5	1.5

The moving speeds of different types of pedestrians under different conditions are shown in Table 3. The evacuees are homogeneous from the aspect of speed according to Section 3.1. In the study of Lu et al. [16], the average speed of pedestrian evacuation was about 1.5 m/s through evacuation experiments. Therefore, we set the speed of all pedestrians as 1.5 m/s in emergency.

4. Case study

4.1. The affiliated pediatric hospital of Fudan University

The affiliated pediatric hospital of Fudan University is one of the top 10 pediatric hospitals in China. The comprehensive hospital has 13 pediatric sub-specialties. The daily outpatient visits can reach 6000 ~ 7000. The pediatric hospital receives at least 15,000 visitors a day because pediatric patients are always accompanied by their parents. The composition of population is complex. The outpatient building has three floors. Most people are waiting outside the clinics on the second and third floors. Pedestrians on the first floor are mainly those who want to leave after the medical treatment, those who want to complete various medical treatment preparations and those who want to see a doctor in departments on this floor.

The layout of the first floor of the outpatient department is shown in Fig. 11. The small black boxes in the hall are internal pillars.

The daily outpatient volume is so large that many people gather in the hospital at the same time every day. The pedestrians near the information desk, calm center, escalator, radiology service desk, registration, charge room and nuclear medicine department on the first floor are more crowded than those in other areas through our practical observations. In addition to waiting or queuing in these areas, some are leaving after the service and some are moving around to receive services. The actual movement of pedestrians is complicated. The observed distribution of pedestrians in various areas is shown in Table 4.

4.2. initial conditions of simulations

CA model is used to simulate the first floor of outpatient department of the pediatric hospital. The two-dimensional spatial layout of simulation is set according to the plane layout in Fig. 12. There are a few patients and medical staff in each department. Patients and their families mostly move or wait outside departments. Therefore, pedestrians in each inner department are not considered. The simulation scenario is simplified accordingly.

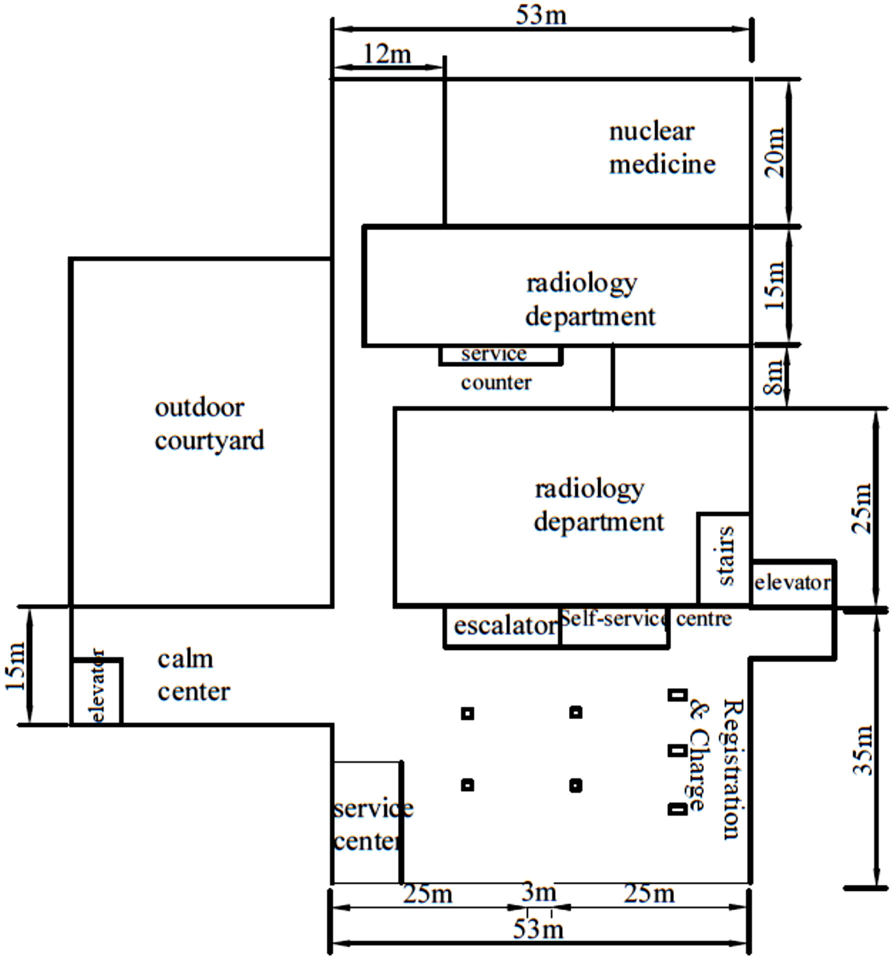

Fig. 11. The ground floor layout of the hospital.

Table 4
Distribution of pedestrians in the pediatric hospital.

Area	Number of pedestrians
Information desk	50～75
Calm center	215～250
Near the escalator	165～225
Registration and Charge room	75～125
Self-service center	35～55
Nuclear medicine	100～150
Radiology desk	100～150
Outpatient service hall	120～170
Corridor	75～100
Elevator	30～50
Total	**965～1350**

In the initial state, 1500 pedestrians are distributed in the whole simulation scene according to the data in Tables 4 and 6. The density near the escalator and the radiology desk is high. The partial zoom in is shown in Fig. 13.

4.3. Defining parameter values

Lu et al. [16] used iteration sequence to find the optimal parameters between simulations and experiments under monotonous variation of parameters. The difference in evacuation time is the smallest whenk_d = 6. Their study is similar to ours. Therefore, k_d in this study is the same with [16]. k_S = 0.6 and k_D = 0.4 are based on Suma et al. [32] and Kirchner et al. [34]. In addition, when

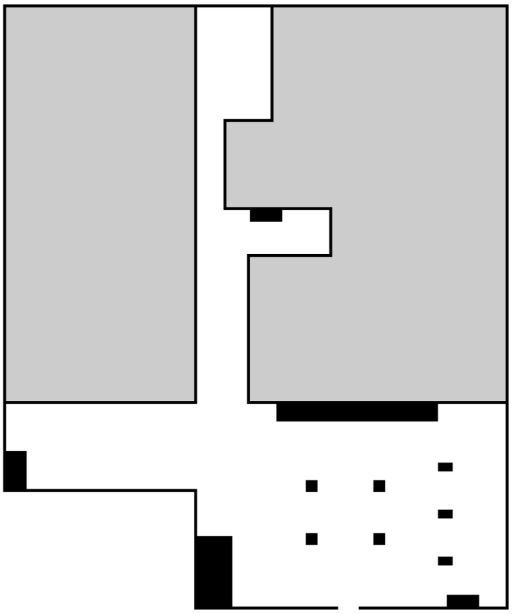

Fig. 12. The simulation scene.

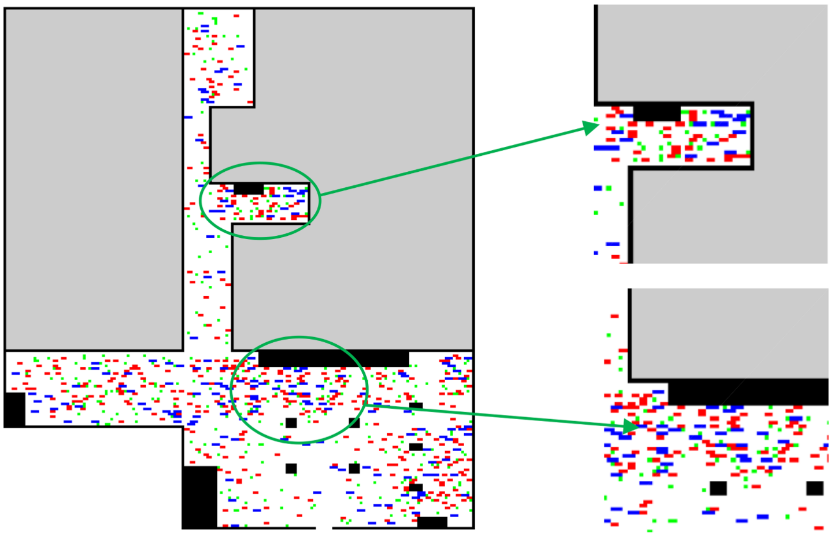

Fig. 13. Initial state of the simulation.

$k_A > 0.1$, the distribution of all pedestrians is in a parallel linear state, which is not in line with the actual situation. When $k_A = 1$, group members could hardly move forward. In our simulations, the best simulation effect is observed when $k_A = 0.03$.

According to our previous study [31] and [32], the evacuation time decreases with the increase of R at first. The parameter R stands for calculation range of the local density field as shown in Fig. 3. It is the least when R is about 4 [31]. Pedestrians can avoid

Table 5
Fixed parameter value.

Parameter	Value
k_S	0.6
k_D	0.4
k_d	6
k_A	0.03
R	4

Table 6
The proportion of different types of pedestrians.

Pedestrian type	Normal	Emergency
Members of G-2	49%	44.1%
Members of G-3	32%	22.4%
Independent pedestrians	19%	33.5%

many congestions and the evacuation efficiency will be improved when R improves. However, Pedestrians may change direction to a longer evacuation path as R continues to increase. In this case, local density field plays a dominant role. Movement space of pedestrians will be wasted due to excessive avoidance of pedestrians. In our study, most pedestrians move in family units because of the cohesive distance between the follower and the leader. Therefore, it is optimal when R is 4 in this study.

The values of fixed parameters are shown in Table 5.

4.4. Overlapping

An adult and an accompanied child share the same cell if there is overlapping.

Children under age 4 are cradled in normal. If a group of three members with child under age 4 actually occupies two cells in simulations, it is treated as a G-2. A group of two members with child under age 4 actually occupies one cell.

Not only children under age 4 are cradled, but children aged 4 to 8 years are also cradled in emergency. 40% of children will be cradled except for those under age 4 who are cradled all the time according to the data in Table 2. The number of both G-2 and independent pedestrian will increase while that of G-3 decreases. Therefore, the proportions of groups of different sizes in both normal and emergency are shown in Table 6.

5. Simulation results and discussion

The total evacuation time is the time from the beginning of evacuation to the last pedestrian leaving the hall. As the number of simulation steps increases, the number of remaining pedestrians are shown in Fig. 14(a). The red curve shows the change in emergency, while the blue one refers to the normal. The average evacuation time of different types of pedestrians is shown in the Fig. 14(b).

The average evacuation time of different types of pedestrians is shown in Table 7. The total average evacuation time is 661.5 steps in emergency while it is 981.0 steps in normal. The evacuation time is reduced by 32.6% compared with that in normal. The overlapping will occur in emergency. Overlapping releases more free space. The groups move first under the priority order. Therefore, the evacuation time of independent pedestrians is not greatly reduced, which is different from that of the groups.

Our research group proposed waiting time [31,33] which referred to the time that pedestrians could not move due to congestion or waiting among group members. It reflects the useless time in the evacuation. The waiting time increases by 1 step when the pedestrian position does not change between the two update steps. The waiting time of pedestrians in the hall is shown in Fig. 15(a). The blue lines represent the waiting time of pedestrians in normal (without the rule of overlapping and speeding up), while the red ones represent the waiting time of pedestrians in emergency. The average waiting time of different types of pedestrians is shown in Fig. 15(b).

The waiting time of various types of pedestrians in emergency is shown in Table 8.

The average waiting time of the G-2 and the G-3 is 40.8% and 35.9% lower in emergency than that in normal, respectively. The

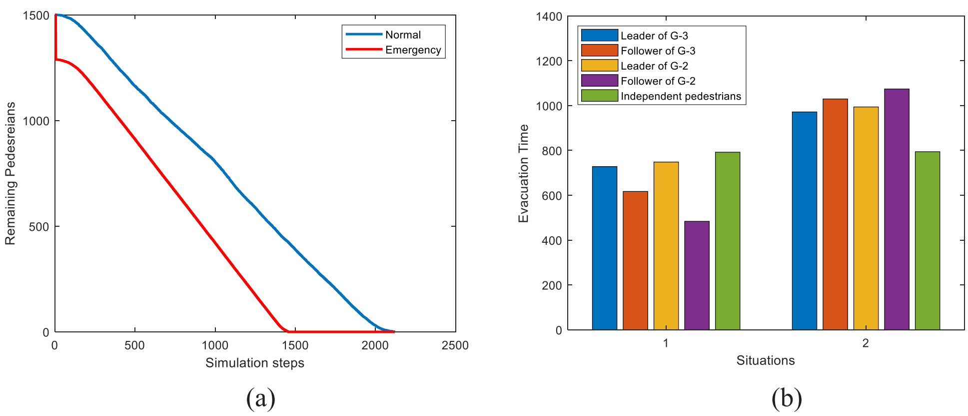

Fig. 14. (a) The number of remaining pedestrians changes with simulation steps
(b) The average evacuation time of different types of pedestrians (1-Emergency situation, 2-Normal situation).

Table 7
The average evacuation time for different types of pedestrians.

Evacuation Time	Emergency	Normal	Reduced proportion
Leaders of G-3	727.9	971.7	25.1%
Followers of the G-3	617.0	1029.5	40.1%
Leaders of G-2	748.2	993.9	24.7%
Followers of the G-2	483.7	1073.9	55.0%
Independent pedestrians	792.1	794.3	0.28%
Total	661.5	981.0	32.6%

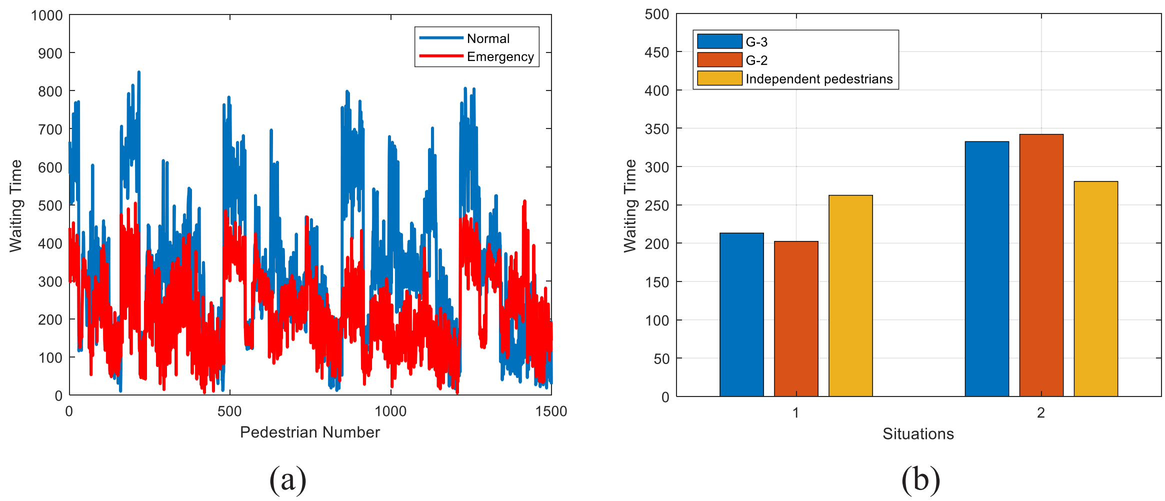

Fig. 15. (a)The waiting time for each pedestrian(b) Waiting time for different types of pedestrians (1-Emergency situation, 2-Normal situation) .

Table 8
Waiting time of group members and independent pedestrians.

Average Waiting Time	Emergency	Normal	Reduced proportion
Members of the G-3	213.2	332.6	35.9%
Members of the G-2	202.4	342.1	40.8%
Independent pedestrian	262.5	280.6	6.5%
Overall waiting time	217.2	327.4	33.7%

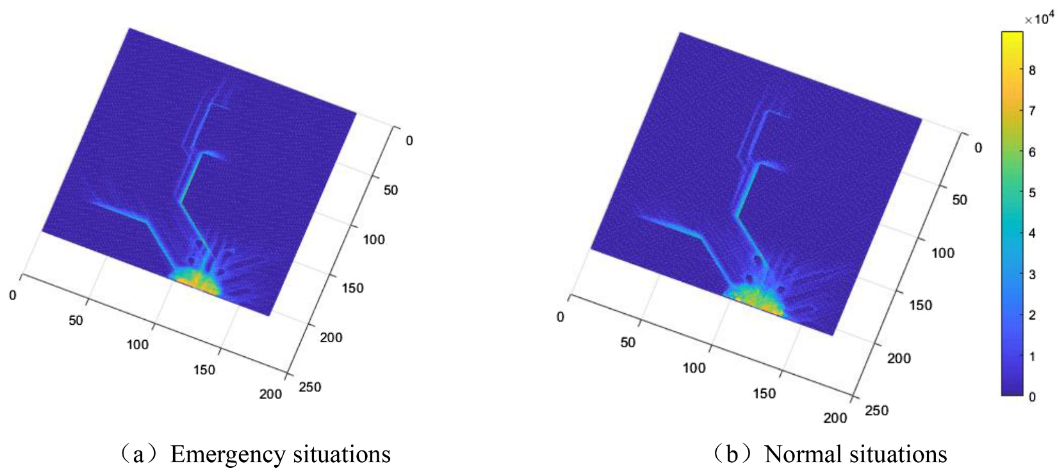

Fig. 16. Space utilization.

average waiting time of the independent pedestrians is also reduced by 6.5% although it does not decline as much as groups. There are two main reasons for the reduction. First, the overlapping and the speeding up are only reflected in group members. In emergency, the number of evacuees is reduced because of the overlapping rule. Second, waiting and backtracking only occur among group members.

The superposition of evacuation paths in emergency is shown in Fig. 16(a), and Fig. 16(b) shows that in normal. The more times the cells are utilized, the color of the cells is closer to yellow. The cell turnover is defined here analogous to the definition of parking turnover [35]. It is the number of times each cell is occupied by pedestrians in a certain period of time. It reflects the space utilization efficiency of each cell. Congestion always occurs near the exit during the evacuation. It can be seen from our simulations that the space utilization efficiency is highest near the exit. The blocking radius near the exit in normal is larger than that in emergency when there is no overlapping rule. It indicates that the overlapping rule has a great impact on evacuation efficiency in the crowded state. Our result is consistent with the findings of Bandini et al. [20].

The obvious phenomenon can be observed that the pedestrians in the back tend to follow the path of the pedestrians in the front. The followers always follow the leaders because of the cohesive distance of the group in transition probability.

6. Conclusion

The evacuation simulations of a pediatric hospital are studied based on an extended CA model in this paper. Groups are taken into account in our model because family unit is the biggest characteristic. There are groups of different sizes and shapes. The size of some groups is changeable due to the overlapping rule. The shape of groups is also changeable because followers always closely follow their leaders. The cohesive distance ensures group members always stay together. The rules of overlapping and speeding up are added. The overlapping really reflects the phenomenon that adults may cradle their children in arms in pediatric hospitals. The speeding up rule reflects the change in the speed of evacuees in emergency. The results show that the total evacuation time and individual waiting time of groups are significantly reduced because the overlapping and speeding up. Evacuation efficiency is also closely related to these two factors. It is important to suggest parents to cradle their young children in arms as much as possible during evacuation.

The study of this paper also has some limitations. In fact, the speed composition of pedestrians in the hospital is complex. Special children such as disabled children were not considered. These conditions should be taken into account in future studies.

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References

[1] X. Yang, H. Dong, X. Yao, Passenger distribution modelling at the subway platform based on ant colony optimization algorithm, Simul. Model. Pract. Theory 77 (2017) 228–244, https://doi.org/10.1016/j.simpat.2017.03.005.
[2] X. Chen, H. Li, J. Miao, S. Jiang, X. Jiang, A multiagent-based model for pedestrian simulation in subway stations, Simul. Model. Pract. Theory 71 (2017) 134–148, https://doi.org/10.1016/j.simpat.2016.12.001.
[3] C. Ahn, J. Kim, S. Lee, An analysis of evacuation under fire situation in complex shopping center using evacuation simulation modeling, Procedia - Soc. Behav. Sci. 218 (2016) 24–34, https://doi.org/10.1016/j.sbspro.2016.04.007 ISSN 1877-0428.
[4] H. Li, T. Thrash, C. Hölscher, R Victor, Schinazi, The effect of crowdedness on human wayfinding and locomotion in a multi-level virtual shopping mall, J. Environ. Psychol. 65 (2019) 101320, , https://doi.org/10.1016/j.jenvp.2019.101320 ISSN 0272-4944.
[5] L. Chen, T.-Q. Tang, Z. Song, H.-J. Huang, R.-Y. Guo, Child behavior during evacuation under non-emergency situations: experimental and simulation results, Simul. Model. Pract. Theory 90 (2019) 31–44, https://doi.org/10.1016/j.simpat.2018.10.007.
[6] W. Liangsheng, Analysis of Pediatric Medical Services in A Second-Level General Hospital or Above, Fujian Medical University, 2018.
[7] L. Yan-ting, F. Liang, W. Lingfang, L. Jiquan, W. Liangchen, Z. Yimin, Development status and problems of pediatric medical complex in Shanghai, China Primary Health Care 32 (04) (2018) 30–32.
[8] H. qi, L. Qili, The pediatric hospital being refreshed - do you feel these pioneering activities? Xinmin Weekly 20 (2018) 1008–5017 p6-9.
[9] Y. Guangjun, Planning a future pediatric hospital at a new starting point, Xinmin Weekly (2017) 1008–5017 23 P44-45.
[10] A.F. Aveni, The not-so-lonely crowd: friendship groups in collective behavior, Sociometry 40 (1) (1977) 96–99, https://doi.org/10.2307/3033551.
[11] M. Moussaïd, N. Perozo, S. Garnier, D. Helbing, G. Theraulaz, The walking behaviour of pedestrian social groups and its impact on crowd dynamics, PLoS ONE 5 (4) (2012) e10047, https://doi.org/10.1371/journal.pone.0010047.
[12] S. Bonneaud, K. Rio, P. Chevaillier, W. Warren, Accounting for patterns of collective behavior in crowd locomotor dynamics for realistic simulations, Transactions on Edutainment VII, Springer-Verlag, 2012, https://doi.org/10.1007/978-3-642-29050-3_110.1016/S0378-4371(01)00141-8.
[13] L.Z. Yang, D.L. Zhao, J. Li, T.Y. Fang, Simulation of the kin behavior in building occupant evacuation based on Cellular Automaton, Build. Environ. 40 (3) (2005) 411–415, https://doi.org/10.1016/j.buildenv.2004.08.005 ISSN 0360-1323.
[14] L. Li-Li, R. Gang, W. Wei, W. Yi, Modeling walking behavior of pedestrian groups with floor field cellular automaton approach, Chin. Phys. B 23 (8) (2014) 654–660.
[15] L. You, J. Hu, M. Gu, W. Fan, H. Zhang, The simulation and analysis of small group effect in crowd evacuation, Phys. Lett. A 380 (41) (2016) 3340–3348, https://doi.org/10.1016/j.physleta.2016.08.012 ISSN 0375-9601.
[16] L. Lu, C.-Y. Chan, J. Wang, W. Wang, A study of pedestrian group behaviors in crowd evacuation based on an extended floor field cellular automaton model, Transp. Res. Part C: Emerg. Technol. 81 (2017) 317–329, https://doi.org/10.1016/j.trc.2016.08.018 ISSN 0968-090X.
[17] L. Crociani, Y. Zeng, G. Vizzari, S. Bandini, S. matters, Modelling, calibrating and validating pedestrian movement considering groups, Simul. Model. Pract. Theory 87 (2018) 73–91, https://doi.org/10.1016/j.simpat.2018.06.001.
[18] Y. Ma, L. Li, H. Zhang, T. Chen, Experimental study on small group behavior and crowd dynamics in a tall office building evacuation, Physica A: Stat. Mech. Appl. 473 (2017) 488–500, https://doi.org/10.1016/j.physa.2017.01.032 ISSN 0378-4371.
[19] J. Drury, C. Cocking, S. Reicher, Everyone for themselves? A comparative study of crowd solidarity among emergency survivors, Br. J. Soc. Psychol. 48 (3) (2009) 487–506, https://doi.org/10.1348/014466608X357893.
[20] Stefania Bandini, Matteo Mondini, Giuseppe Vizzari, Modelling negative interactions among pedestrians in high density situations, Transp. Res. Part C: Emerg.

Technol. 40 (2014) 251–270, https://doi.org/10.1016/j.trc.2013.12.007 ISSN 0968-090X.

[21] J. James, The distribution of free-forming small group size, Am. Sociol. Rev. 18 (1953) 569–570 5 (Oct..

[22] J. Zhang, W. Song, X. Xu, Experiment and multi-grid modeling of evacuation from a classroom, Physica A: Stat. Mech. Appl. 387 (23) (2008) 5901–5909, https://doi.org/10.1016/j.physa.2008.06.030 ISSN 0378-4371.

[23] M. Haghani, M. Sarvi, Z. Shahhoseini, M. Boltes, Dynamics of social groups' decision-making in evacuations, Transp. Res. Part C: Emerg. Technol. 104 (2019) 135–157, https://doi.org/10.1016/j.trc.2019.04.029 ISSN 0968-090X.

[24] Cornelia von Krüchten, Andreas Schadschneider, Empirical study on social groups in pedestrian evacuation dynamics, Physica A: Stat. Mech. Appl. 475 (2017) 129–141, https://doi.org/10.1016/j.physa.2017.02.004 ISSN 0378-4371.

[25] Y. Song, K. Xie, W. Su, Mechanism and strategies of post-earthquake evacuation based on cellular automata model, Int. J. Disaster Risk Reduct. 34 (2019) 220–231, https://doi.org/10.1016/j.ijdrr.2018.11.020 ISSN 2212-4209.

[26] C. Burstedde, K. Klauck, A. Schadschneider, J. Zittartz, Simulation of pedestrian dynamics using a two-dimensional cellular automaton, Physica A: Stat. Mech. Appl. 295 (3–4) (2001) 507–525 IssuesISSN 0378-4371.

[27] Y. Zheng, X. Li, N. Zhu, B. Jia, R. Jiang, Evacuation dynamics with smoking diffusion in three dimension based on an extended Floor-Field model, Physica A: Stat. Mech. Appl. 507 (2018) 414–426, https://doi.org/10.1016/j.physa.2018.05.020 ISSN 0378-4371.

[28] C.-J. Jin, R. Jiang, W. Wei, D. Li, N. Guo, Microscopic events under high-density condition in uni-directional pedestrian flow experiment, Physica A: Stat. Mech. Appl. 506 (2018) 237–247, https://doi.org/10.1016/j.physa.2018.04.030 ISSN 0378-4371.

[29] A.R. Larusdottir, A.S. Dederichs, Evacuation of children: movement on stairs and on horizontal plane, Fire Technol. 48 (2012) 43–53, https://doi.org/10.1007/s10694-010-0177-6.

[30] H. Najmanova, E. Ronchi, An experimental data-set on pre-school, Fire Technol. 53 (2017) 1509–1533, https://doi.org/10.1007/s10694-016-0643-xChildren Evacuation.

[31] B. Zou, C. Lu, S. Mao, Y. Li, Effect of pedestrian judgement on evacuation efficiency considering hesitation, Physica A: Stat. Mech. Appl. (2019) 122943, , https://doi.org/10.1016/j.physa.2019.122943 ISSN 0378-4371.

[32] Y. Suma, D. Yanagisawa, K. Nishinari, Anticipation effect in pedestrian dynamics: modeling and experiments, Physica A: Stat. Mech. Appl. 391 (1–2) (2012) 248–263, https://doi.org/10.1016/j.physa.2011.07.022 IssuesISSN 0378-4371.

[33] B. Zou, C. Lu, Y. Li, Simulation of a hospital evacuation including wheelchairs based on modified cellular automata, Simul. Model. Pract. Theory (2019) 102018, , https://doi.org/10.1016/j.simpat.2019.102018.

[34] A. Kirchner, A. Schadschneider, Simulation of evacuation processes using a bionics-inspired cellular automaton model for pedestrian dynamics, Physica A 312 (1–2) (2002) 260–276, https://doi.org/10.1016/S0378-4371(02)00857-9.

[35] A. Borovskoy, E. Yakovleva, Simulation model of parking spaces through the example of the Belgorod agglomeration, Transp. Res. Procedia 20 (2017) 80–86, https://doi.org/10.1016/j.trpro.2017.01.019 ISSN 2352-1465.