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A Cellular Automaton Model for Exit Selection Behavior Simulation during Evacuation Processes

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Abstract

Exit selection behavior is important for evacuation processes and safe facility design. Pedestrians’ ability to select an exit route is affected by many factors, and will also impact on evacuation efficiency. It should not be neglected when modeling evacuation. In the case of asymmetric exits and distribution of pedestrians, an important issue is how to identify a pedestrian’s target when performing simulations. However, this has not been well investigated, especially in discrete models. In this regard, we tend to investigate pedestrian exit choice behavior by integrating the least effort algorithm with a cellular automaton model. The distance to exits and crowd density around exits are involved. Simulations are conducted in a two-exit room. Evacuation time in scenarios where there are some special distributions of pedestrians is compared with that in scenarios where pedestrians are randomly distributed. The influence of the weighted value of the distance to exits or crowd density around exits on evacuation time is also studied. Useful suggestions are provided. The effect of locations of exits on evacuation time and the cumulative number of egress pedestrians are further investigated. Results demonstrate that two exits located in different walls, especially in symmetrical walls, are helpful in evacuation processes. This result is in line with that in other references. It is hoped that this work will be helpful in improving evacuation rules of discrete models in multi-exit situations.

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Keywords: pedestrians, exit selection, model, simulation, evacuation

1. Introduction

With the increasing number of unexpected events (e.g., fires, explosions and stampedes) in recent years, pedestrian and evacuation dynamics has attracted a great deal of attention. Pedestrian evacuation is one of the most useful ways to guarantee human safety under emergency situations. It involves a complex system which includes heterogeneous individuals and interactions between pedestrians or between pedestrians and the environment. During this process, different pedestrian behaviors can be discovered, such as congestion, the “faster-is-slower effect” and exit selection behavior. In fact, multi-exits are frequently observed in buildings. Collective phenomena around exits and pedestrians’ exit selection behavior are important for the design of buildings, such as a door’s width and the number of doors in a room. Therefore, study on exit selection behavior is necessary.

To date, both experimental and modeling methods have been adopted to investigate pedestrian evacuation processes. However, models are more convenient and flexible to repeat these processes than experiments. Many models have been proposed to simulate evacuation behavior. In a broad classification, they can be divided into macroscopic models, mesoscopic models and microscopic models [1]. Human movement in macroscopic models resembles a fluid flow, and is described...
through partial differential equations which are principally for the analysis of the evolution of density and speed [2]. Macroscopic approaches pay more attention to rules governing the global behavior of pedestrians, and are usually difficult to reflect individual diversities. Mesoscopic models are a combination of macroscopic and microscopic methods. They focus on groups of pedestrians rather than a single pedestrian. Each group is endowed with behavioral rules. This method is of benefit for analyzing real-time pedestrian flow in public places or modeling regional pedestrian traffic [1]. Nevertheless, it cannot reproduce emergent behavior [3]. In contrast, microscopic models are able to create individual behavior and interactions. They are usually divided into four kinds, i.e., queuing network models, multi-agent models, physical based models and cellular based models [1]. Here, cellular based models are the most widely utilized to simulate pedestrian movement in discrete space and time [4]. Simple rules, such as transition probabilities, are employed to guide discrete movement. The lattice gas model [5], floor field model [6], multi-grid model [7], three-dimensional cellular automaton model [8], etc. are according to cellular automata (CA), and have been modified to investigate pedestrian and evacuation dynamics under different scenarios, such as rooms with multi-exits. Aik and Choon [9] proposed a modified CA model to study pedestrian evacuation processes in rooms with obstacles. This model involved human emotions, crowd density around an exit and pedestrians’ ability to choose a suitable exit. Chen et al. [10] also performed simulations and experiments of pedestrian evacuation in a classroom with two exits. They considered the effects of distance to an exit, repulsion between pedestrians, etc. on pedestrians’ exit choice. In fact, exit selection behavior can be affected by many factors in real evacuation processes [11]. The distance to an exit and the number and density of pedestrians within their view field are primary factors that affect pedestrians’ exit choice [12]. However, these factors are always not comprehensively considered in many CA models. How to decide pedestrians’ targets in a multi-exit room has not been well studied. This paper aims to present an improved CA model which simulates exit selection behavior of pedestrians in a two-exit room. This model is established according to the least effort algorithm. Crowd density is incorporated into it. The remaining part of this paper is organized as follows: Sect. 2 introduces detailed rules of the proposed model; Sect. 3 analyzes and discusses simulation results; Finally, conclusions are reported.

2. Model description

This model is defined in a cellular space where each cell is a similar square area of 0.4 m × 0.4 m (a typical size of pedestrians). Each cell may be empty or occupied by a pedestrian or an obstacle. Pedestrians cannot overlap with each other. Here, the Moore neighbourhood is employed, i.e. pedestrians can move to one of their eight neighbouring cells (x, y) at each time step (see Fig. 1). The transition probability is \( P_{x,y} \) which is calculated in the following [13, 14].

\[
P_{x,y} = NM_{x,y}
\]  
(1)

\[
N = \frac{1}{\sum M_{x,y}}
\]  
(2)

\[
M_{x,y} = (1 - I_{x,y}) \frac{L_{\text{min}}}{L_{x,y}}
\]  
(3)

where \( N \) is a normalization factor in order to ensure that the sum of \( P_{x,y} \) of eight neighbouring cells is 1. Parameter \( L_{x,y} \) \((L_{x,y} \neq 0)\) represents the Euclidean distance between neighbouring cell \((x, y)\) and a target (e.g., an exit). \( L_{\text{min}} = \text{Min}(L_{x,y}) \). \( L_{\text{min}} / L_{x,y} \) denotes the ratio between the minimum of \( L_{x,y} \) and the value of \( L_{x,y} \). \( I_{x,y} = \{0, 1\} \) where 0 and 1 represent that cell \((x, y)\) is unoccupied and occupied, respectively. After all values of \( P_{x,y} \) are obtained, they are ranked in order to ensure that the largest value of \( P_{x,y} \) is always selected, i.e. the least effort during pedestrian movement is reflected. Here, the method in Ref. [13] is employed to complete this process, i.e. a normal distribution where the mean value is 1 and standard deviation is 0.5 is used to create random numbers which are rounded to the nearest integer index numbers.
In a room with two exits, pedestrians have two destinations. The problem on how to select exits needs to be solved. Here, the probability \( E_i \) that a pedestrian select an exit \( (i = 1 \text{ or } 2) \) is related to his/her distance to this exit and crowd density around it. This probability is shown as follows:

\[
E_i = (1-\alpha)p_1 + \alpha p_2,
\]

\[
P_1 = \begin{cases} 
\frac{D^2_{x,y}}{D^2_{x,y} + D^2_{x,y}}, & i = 1, \\
\frac{D^1_{x,y}}{D^1_{x,y} + D^2_{x,y}}, & i = 2,
\end{cases}
\]

\[
P_2 = \begin{cases} 
1 - \frac{N^1_k}{N_{\text{sum}}}, & i = 1, \\
1 - \frac{N^2_k}{N_{\text{sum}}}, & i = 2.
\end{cases}
\]

Here, parameter \( \alpha \) reflects the degree of impatience of pedestrians during an evacuation process, as this is an important factor in exit choice \([9]\). \( D^1_{x,y} \) and \( D^2_{x,y} \) are respectively the distance of a pedestrian’s neighbouring cell \((x, y)\) to exits 1 and 2. \( N^1_k \) and \( N^2_k \) respectively denote the number of other individuals in the room who are nearer than individual \( k \) to exits 1 and 2. \( N_{\text{sum}} \) represents the number of pedestrians in the room at each time step. Eq. (4) indicates that a decrease in the distance of pedestrian \( k \) to exit \( i \) and congestion around exit \( i \) will induce an increase in the probability of selecting this exit.

Accordingly, updating rules for pedestrian movement and exit selection behaviour are summarized in the following:

1. Identify each pedestrian’s target exit at each time step, i.e. calculate probability \( E_i \). Then obtain transition probabilities of each pedestrian’s neighbouring cells \((P_{x,y})\), and thus each pedestrian’s target cell at each time step is determined.

2. Random shuffle update is employed to alter pedestrians’ locations in a room. If they reach exits, remove them from the room. When there is no pedestrian in the room, the evacuation process will finish.

3. Simulation results and analysis

The proposed model is tested in a room with two exits. The size of the room is 24 × 18 cells (namely 9.6 m × 7.2 m). Each exit occupies 2 cells. Fig. 2 shows a layout of the room where the walls are represented in grey. Two initial non-uniform distributions of 60 pedestrians in the room are involved in Fig. 2(1) and (2). Each time step is 0.4 s.

As the process of exit selection and the influence of parameter \( \alpha \) on evacuation time in this model are clearly discussed in Ref. \([14]\), we focus on the difference in evacuation time under two scenarios in Fig. 2(1) and (2) between our proposed model and another rule (i.e., pedestrians randomly selecting an exit). Fig. 3(a) shows evacuation time of pedestrians in scenarios (1) and (2) in Fig. 2 according to our proposed model, while Fig. 3(b) depicts evacuation time of pedestrians who select an exit randomly. As analysed in Ref. \([14]\), evacuation time is the largest when \( \alpha = 0 \) (i.e. the weighted value of the distance to an
exit is the largest), because all pedestrians in both scenarios will egress through a same exit, resulting in the severest congestion. Therefore, we set $\alpha = 0$. A total of 500 runs are conducted in each scenario. From Fig. 3, it is evident that evacuation time in our model is much smaller than that of pedestrians who randomly select an exit under the same scenario. This is due to that pedestrians will often alter their targets during the whole evacuation process if their targets are random, increasing their egress time. However, this phenomenon is not realistic in real evacuation situations. Therefore, our proposed method can solve this problem.

In fact, the non-uniform distributions of 60 pedestrians in the room described above are just special cases (namely scenarios (1) and (2)). What is the result if pedestrians are randomly distributed? Here, evacuation time in scenarios (1) and (2) is compared with that in the scenario where pedestrians in the room are randomly distributed (namely scenario (3)). Fig. 4 depicts comparisons of evacuation time under the effect of $\alpha$ in these three scenarios. It is evident that the value of $\alpha$ has an influence on evacuation time in scenarios (1) and (2), i.e. there is a decrease in evacuation time with an increase in the value of $\alpha$. However, it impacts little on evacuation time in scenario (3). This is owing to that changing the value of $\alpha$ will alter the weighted value of the distance to an exit or crowd density around an exit during pedestrians’ exit selection process. This effect is more marked in scenarios (1) and (2) where pedestrians are in special places of the room than in scenario (3). In general, a larger value of $\alpha$, i.e., increasing the weighted value of crowd density around an exit, is more helpful in evacuation processes, especially in a scenario where pedestrians are not uniformly distributed.

Fig. 2. The layout of the room and two initial distributions of pedestrians in it. Blue full circles represent pedestrians. The walls are marked in grey.

Fig. 3. Evacuation time in two scenarios corresponding to Fig. 2(1) and (2): (a) in our proposed model; (b) when pedestrians randomly select an exit.
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Besides the distribution of pedestrians, study on locations of exits in a room is also necessary for the suitable design of buildings. As described in Ref. [14], if two exits are located in the same wall, the optimal exit separation is $0.3D$ where $D$ is the length of the wall. However, the relationship between different locations of exits in a multi-exit room and evacuation time has not been investigated. As illustrated in Fig. 5, we discuss three situations where the locations of two exits are different, and compare evacuation time in these three situations. Here, 60 pedestrians are randomly distributed in rooms, and $\alpha = 0.6$. The sizes of the rooms are the same with those described above. Fig. 5(d) shows that evacuation time in situation (c) is the largest, while it is the smallest in situation (a). This is due to that pedestrians are easy to gather around two exits during the evacuation process, and two exits located in the same wall will further induce congestion. This result is consistent with that in Ref. [15]. Therefore, when exits are located in different walls, especially symmetrical walls, rather than the same wall, the efficiency of evacuation processes will be improved.

Fig. 5. Locations of two exits alter in a room: (a) exits A and B are respectively in the centres of walls above and below; (b) exits A and B are respectively in the centres of walls above and the right wall; (c) both exits A and B are in the right wall. (d) Comparisons of evacuation time in these three situations.
According to the layouts in Fig. 5(a)–(c), we further investigate time evolution of the cumulative number of evacuees in Fig. 6. It is observed that irregular outflow is reflected, especially in situation (c). This trend is in line with that in Ref. [16]. Moreover, the difference in evacuation time in three situations described above is also shown in this figure. Therefore, our model is available to simulate exit selection processes during evacuation.

4. Conclusions

In this paper, we have proposed a cellular automaton model to simulate pedestrians’ exit selection behaviour during evacuation processes. The impatience of individuals, distance to exits and crowd density around exits are involved in this model. According to transition probabilities, pedestrian movement is performed. First, we analyse evacuation time in scenarios where pedestrians are distributed in given places of a two-exit room. Results of our proposed model are compared with those when pedestrians randomly select an exit. It was found that evacuation time of pedestrians who randomly select an exit is much larger than that in our model. This indicates that our proposed rules can serve as a method to improve exit-selection models. Then, the effect of different values of parameter $\alpha$ on pedestrians’ evacuation time in three scenarios where the distribution of pedestrians alters is obtained. It is observed that the value of $\alpha$ has little influence on evacuation time when pedestrians are randomly distributed in a room. An increase in the weighted value of crowd density around an exit is beneficial to evacuation processes. Finally, the effect of different locations of exits on evacuation time is examined. Results are in accordance with those in other references. The cumulative number of evacuees as a function of time is also identified. These results suggest that our proposed model is available to simulate exit selection behaviour.

Of course, more experimental data are required to further improve our model in future work. Moreover, this model with simple rules can be applied in more complicate scenarios.

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References


Fig. 6. Time evolution of the cumulative number of evacuees.