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*Research Article*

# Modeling Human Evacuating Behavior in Limited Space Based on Cellular Automata Model

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The study of evacuation for buildings with limited space is an important part of improving evacuation efficiency and preventing stampedes. A building evacuation model was proposed based on cellular automata simulation considering different crowd states. Different flow sizes under layout environments with the same facilities as well as evacuation efficiency, bottleneck area density, and escape routes choice under the orderly and disorderly distribution conditions have also been analyzed. The results show that the initial disorderly distribution state is superior to the orderly distribution state in terms of the evacuation efficiency index. The former provides evacuees with maximum room for the corridor and the exit, with the overall evacuation density being lower than that of the latter. Evacuation along the central corridor provides more room compared to that of the two flanks, which explains why evacuees prefer to occupy the central area when space is limited, and this is detrimental to the moving capacity.

## 1. Introduction

Evacuation within limited spaces has always been one of the popular issues that allow for professional research. The objective of the building evacuation is to minimize the evacuation time and optimize the escape route and facility layout. In specific disasters, such as fires and earthquakes, the evacuation could be a complex process due to lots of evacuees and differentiating decision behaviors. Some literature has exhibited an interest in investigating this issue in conjunction with the safety of some buildings [1, 2]. Because of limited space facilities, there are many uncertain factors in the process of flow evacuation, including physical conflicts that lead to evacuation chokepoints, where secondary disasters like stampede frequently occur. Past events showed that unless appropriate guidance is given, pedestrians may select inappropriate escape routes, which may result in push and squeeze or trample. It is important to study the choice of escape routes and the layout of facilities within the limited space, which is also a key factor in ensuring the safety of the evacuation, the reasonable layout of building facilities, and the improvement of the congestion management level.

Several methods have been proposed to optimize and evaluate the evacuation process. The predominant paradigms of simulation-based approaches [3–5] and optimization models [6, 7] are widely used to optimize and evaluate evacuation plans. The simulation method is usually used to test the evacuation performance of complex buildings and transportation hubs and to evaluate the dynamic evacuation process. Therefore, it is also suitable to simulate pedestrian flow and escaping the behavior of crowds. Some simulation tools, such as Legion, VISSWALK, SimWalk, and AnyLogic, having been developed are suitable to simulate decision-making, human cognition, and social behavior [8], but many aspects of human behavior are not well understood and analyzed, particularly in design schemes optimization and emergency scenarios [9, 10]. Simulations can identify key points that can lead to confusion and disorientation to identify the poor design of the built environment and emergency response systems. However, most models do not provide solutions for the optimization of the overall evacuation process.

The comprehensive research regarding existing specifications for building facilities layout and the choice of escape routes are still in the exploratory stage. For all these reasons, it is believed that the reliability and accuracy of the existing crowd simulation programs for practical design purposes are still limited.

In this paper, we proposed a model for crowd evacuation in limited space based on different crowds gathering mode. In the limited architectural space, due to evacuation time, space, obstacle layout, and other factors, it maybe makes the problem complex that the heterogeneity of the human behavior that different individuals may exhibit in a certain evacuation scenario. The proposed model is calibrated on simulation and applied to real case studies.

## 2. Literature Review

Many works within the recent years have been carried out to analyze pedestrian behavior and enhance the safety strategies of limited architectural space [11–13]. The analysis of the egress behavior is the key link to ensure the evacuation safety, optimize the facilities layout, and keep the high level of congestion management [14, 15]. The human escaping behavior could be represented in many ways by simulation [16]. Earlier models simulated the evacuees as a continuous homogeneous mass that behaves as a fluid flowing along the corridors [17, 18], as far as both pedestrian movement and trip maker decision were concerned [8, 19]. These simulation models were typically less accurate in describing pedestrian movement [19]. The individual behavior of people is determined by their own characteristics and external environment, and the influence of surrounding obstacles and the interaction of the crowd play a very important role. The microsimulation focuses on the movement and interaction of the crowd [20, 21]. Typical microscopic models include agent-based simulation [22–24], social force model [25, 26], cellular automata model [27, 28], multigrid model [29], floor fluid model [30], and particle model [31]. The pedestrians may have a differentiated level of familiarities with the architectural space and choose their escape routes, which are not necessarily the shortest path [32, 33].

One of the essential tasks of evacuation in a building is to represent the inherent link between facilities layout and human behavior [34, 35]. The pedestrians' path finding behaviors in buildings and channels have been mainly focused on [36, 37], and the behavior differences in path finding regarding the dynamic spatial availability have been considered [38, 39]. Rogsch et al. considered the difference in spatial knowledge of people in the building and analyzed the evacuation efficiency [12, 40]. Pedestrians may escape according to the optimal route they choose and constantly judge and adjust the route according to their physical and psychological characteristics [33]. Scholars have looked at this problem from different perspectives, such as pedestrian simulation in the different facilities [40, 41], investigating features analysis of crowd behavior in complex maneuvers [10, 42]. The lack of empirical data and the closure of industry data are the main reasons for this phenomenon, hindering the validation and calibration of existing models [43, 44]. Previous studies have partially addressed the lack of interpretive data by providing selective data, conducting experimental studies in relatively simple geometries, or monitoring the actual movement of pedestrians in a crowd [45]. In addition, some scholars have analyzed the feedback mechanism from the perspective of dynamics and uncertainty theory [46–48].

However, the spatial accessibility of the building could be varied due to overcrowds or uncertain conditions, and individualized path choices concerning the human awareness of the predictable change were not fully described. The study on the facilities layout of the building is still in the exploratory stage, and there is an obvious difference in pedestrian behavior under different schemes, which has a direct effect on the evacuation efficiency.

Based on relevant studies and existing norms, there is little consideration given to the group behavior and individual behavior of evacuated people, and the study on the utility and behavior of route selection is insufficient. In this paper, a pedestrian safety evacuation model in finite space is established, and the evacuation efficiency, bottleneck density, and path decision-making of pedestrians in different clustering modes under different schemes are simulated and analyzed.

## 3. The Crowd Evacuation Model Based on the Cellular Automata considering the Different Crowd Gathering Modes

This section presents the basic pedestrian evacuation model we defined for investigating different crowd gathering situations. The model is essentially based on the cellular automata (CA) model approach; nonetheless, for simplicity, we will adopt the agent term to discuss the behavior of pedestrians.

This section gives the basic pedestrian evacuation model we defined for investigating different crowd congregations. The model is based on cellular automata (CA); however, for simplicity, we will use proxy terms to discuss pedestrian behavior.

### 3.1. The Setting of the Visual Areas and Moving Directions.

The model environment is represented by discrete square cells, such as the CA model, whose size is 40 cm × 40 cm. Each cell is connected to other cells according to neighborhood functions. In the basic model, we assume that the Moore neighborhood includes all the units around the unit under consideration, even in the diagonal direction. However, we separate out the subset of neighbors.

The status of the unit cell is either occupied or vacant. The model annotates the space with different tags. These tags are $M$ groups of unit C and have the ability to assign roles to these units. The model assumes the following: (i) the initial area and location (unit) of pedestrian are generated at one time or have a certain frequency distribution; (ii) destination is the place where the pedestrian wants to go, final or intermediate.

The destination is associated with the path field, which indicates the path between each cell in the environment and the destination. Start areas are more complicated: they contain indications for a pedestrian generation. The start area also contains information about the type of pedestrian it must generate, such as destination and related parameters. Each cell can take different forms of wall, facilities, and flow and own 8 neighborhoods. In each simulated step, the entity can only be moved into an adjacent cell or remain in the original cell (see Figure 1):

$$\begin{gathered} \text{Env} = \{\text{Cell}(i,j)\}, \quad \forall \text{Cell}(i,j) \in \text{Cell}, \\ \mu_{i,j} = \begin{cases} 1, & \text{occupied}, \\ 0, & \text{unoccupied}. \end{cases} \end{gathered} \tag{1}$$

### 3.2. *The Setting of Strategy.*

The simulation time is set to discrete. According to the step size, we set the maximum speed of pedestrians to 1 cell per step. Therefore, we can calculate the number of seconds of a single time step [9]. Based on these assumptions, we have a ratio of 3 to 4 steps per second. In order to better simulate the high-density population, we adopted a disorderly sequential update scheme to activate the behavior of agents [49].

In addition to identifiers, pedestrian characteristics can be identified by two pieces of information about their current and past locations:

$$\text{pedestrian: } \{\text{id}, \text{position}, \text{oldDirection}, \text{path}\}. \tag{2}$$

The location is the current cell of the agent. The oldDirection is the last action selected. Path is a specific path field indicating the destination of the pedestrian.

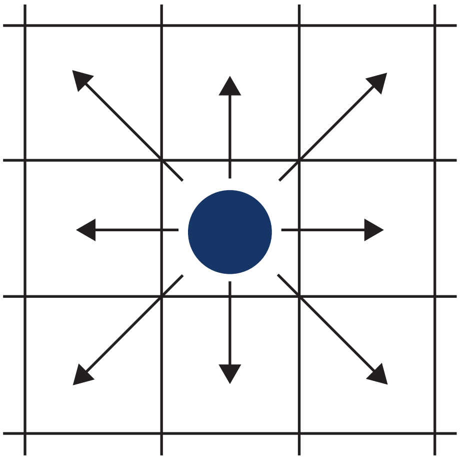


Figure 1: Moving setting and distributive rate.

### 3.3. *The Function: Linking Perceptions to Actions.*

At each time step $t$, agents select their next action by assessing the effectiveness of all acceptable actions $L(x, y)$. The calculation method of action probability adopted by the model is different from the traditional CA model. Moreover, we separate utility probability and action probability so that different types of pedestrians can realize different selection functions.

According to the rules of the moving direction of cell automata, there are eight-cell visual areas that include $V_{ij}^k$, $k = 1, 2, \ldots, 8$ on behalf of the eight clockwise. For example, $V_{ij}^3$ cell (i, j) points in the direction of the eastern visual area containing vacant cell automata and the visual area referred to that visible to pedestrians. For instance, the eastern visual area mainly contained 12 cells, among which 4 were occupied; $V_{ij}^3 = 8$ (see Figure 2).

For each step, the rate is calculated as follows regarding 8 directions moving into a yet unoccupied cell:

$$\begin{gathered} PV_{ij}^k = \exp\left[\omega_D D_{i-1,j} + \omega_V V_{i-1,j}^k + \sum_{m\in k}\left(\omega_C C_r^m + \frac{\omega_E}{E_{i-1,j}^m}\right)\right]\left(1-\mu_{i-1,j}\right)\xi_{i-1,j}, \\ P_{ij}^k = \frac{PV_{ij}^k}{\sum_{\forall k} PV_{ij}^k}, \quad k = 1, 2, \ldots, 8, \\ D(i,j) = \frac{L(x,y) - L(m,n)}{\sqrt{(m-x)^2 + (n-y)^2}}, \end{gathered} \tag{3}$$

where $L(x, y)$ is the estimated optimal utility between Cell$(i, j)$ and exit. $D_{i,j}$ is the directional parameter, while the weight coefficient value is $\omega_D \in [0, 1]$. The former is not subject to time but to the decision-making ability of evacuees. It is dependent on two circumstances: if evacuees are completely familiar with the exit direction and the surrounding environment $\omega_D = 1$; conversely, $\omega_D = 0$. $D_{i,j}$ depends on the exit or the location of the labeled exit, which is the direction all evacuees may move towards. When the escaping direction is too crowded to leave a vacant cell, evacuees may be misled by the visual area $V_{i-1,}$ jk to make a personalized escape route. $C_r^m$ referred to moving capacity per unit of time, which is defined by available cells within the unit of time under the influence of radius areas. $\omega_C$ refers to its corresponding sensitivity parameters, for a single exit, $\omega_C = 0$. $E_{i,j}^m$ refers to the Euclidean distance. Based on the model, simulation analysis is carried out in different environments as there is a conflict between the exit and escape

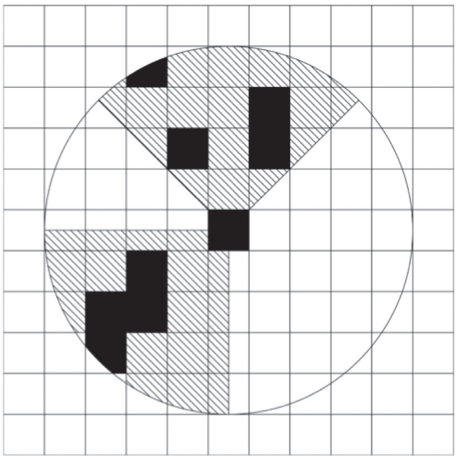


Figure 2: Moving direction and cell visual areas calculation layout.

routes choice. When few persons simultaneously enter the same cell, the optimal synthetic distribution principle is followed: the closer to the cell, the more likely to occupy it.

*3.4. Personalized Evacuation Utility Function.* In the process of crowd evacuation within the limited space, there are some differences as regards the judgment of section resistance: due to individuality, there are obvious response differences. The calculation of $L(x, y)$ involves three factors, namely, relative service level, barrier resistance, and physical factor. Given that these three factors are in a linear relationship with optimal utility (see equation 4), the nonlinear relationship can also be adopted in practice:

$$L(x, y) = \sum_k c_k L_k(x, y). \tag{4}$$

$L_k(x, y)$ represents the utility value of the different path attributes. $c_k$ refers to the relative weight, that is, the importance of each factor. Not all weight coefficients in the model are determined by observed behaviors as the weight only reflects relative importance. $c_k$ is mirrored in the groups of evacuees: different groups lead to different exits and variant $c_k$.

*3.4.1. Congestion Degree.* Evacuees may take the congestion degree of the path ahead into consideration before deciding which way to move ahead. Congestion degree is mainly related to low density and speed within the channel. The density difference between designated areas and the intermediate point of the path ahead should be used to judge how crowded it is, considering that the flow speed is greatly affected:

$$L_1(x, y) = \frac{\rho_L}{\rho_A}. \tag{5}$$

$\rho_L$ is the evacuees-centered average density of $i$ within currently limited areas; $\rho_A$ is the average flow density within the adjacent areas ahead. The greater the density difference between adjacent areas and currently limited areas, the greater the congestion index.

*3.4.2. Barrier Resistance Factor.* During the evacuation, there are all kinds of barriers within the model area, such as walls, desks, chairs, and benches. Within a certain distance and in the direction of moving, barrier resistance utility $L_2(x, y)$ and distance between the barrier and the flow refer to monotone decreasing function (see Figure 3). Within the limited space, given the strong barrier resistance impact, barrier resistance factor and barrier distance should be defined as an exponential function (see equation 6):

$$L_2(x, y) = g_m(\mathrm{d}(O_m, x)), \tag{6}$$

$$\begin{aligned} L_2(x, y) &= a_m \exp\left(-\frac{\mathrm{d}(O_m, x)}{b_m}\right), \\ \mathrm{d}(O_m, x) &= \min_{y \in O_m}\{|x - y|\}. \end{aligned} \tag{7}$$

As seen from the equation, the distance $\mathrm{d}(O_m, x)$ between evacuees and barriers are the shortest and most effective. Parameters $a_m > 0$ and $b_m > 0$ refer to barrier-affected areas and their values depend on the barrier type.

Considering the various factors mentioned above, personalized evacuation utility function under any exigency is as follows:

$$L(x, y) = c_1 \frac{\rho_L}{\rho_A} + c_2\left[\omega_1 a_m \exp\left(-\frac{\mathrm{d}(O_m, x)}{b_m}\right)\right]. \tag{8}$$

Functions $c_1$ and $c_2$ can be defined by the actual value.

*3.5. Experimental Scheme*

*3.5.1. Condition for the Initial Layout of Building Facilities.* The building is 8.4 m long and 7.55 m wide (see Figure 4). There are 41 tables and 41 chairs. The width of the aisles is 1.25 m. The width of the door is 0.8 m, and the capacity is 41 persons under normal conditions.

*3.5.2. Initial Gathering Mode for Crowd Evacuation.* In the initial state, there are two kinds of crowd layout: orderly distribution and disorderly one. The former refers to a sedentary state including meeting and lecture (see Figure 5), and the latter refers to a restless state including those randomly distributed in various parts of the building during free time (see Figure 6). Based on different distribution states, there are six situations where the initial numbers of the crowd are 10, 15, 20, 25, 30, and 35, respectively.

## 4. Results and Discussion

The features of the evacuating crowd show that evacuees prefer the most convenient exit or channel. In the same building space, different gathering modes and crowd distribution conditions lead to personalized evacuation with different places to occupy.

*4.1. Different Gathering Modes and Flow Size-Based Evacuation Time Density Analysis.* The difference between orderly distribution and disorderly distribution is analyzed in terms

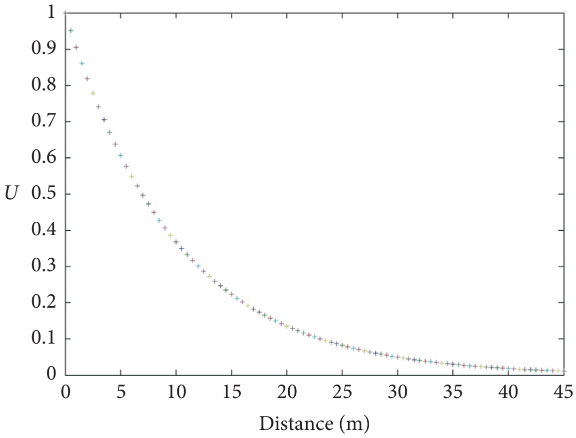


Figure 3: Barrier distance correlative function.

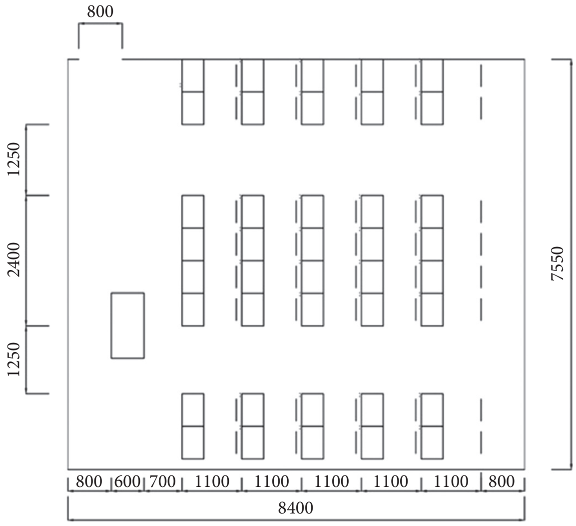


Figure 4: Initial building layout.

Figure 5: The initial numbers of the crowd for orderly gathering modes. (a) 10p. (b) 15p. (c) 20p (d) 25p. (e) 30p. (f) 35p.


(a) (b) (c)

(d) (e) (f)

Figure 6: The initial numbers of the crowd for disorderly gathering modes. (a) 10p. (b) 15p. (c) 20p. (d) 25p. (e) 30p. (f) 35p.

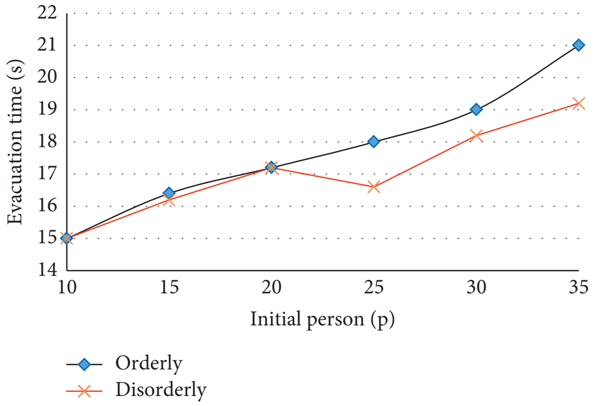


Figure 7: Contrast of evacuation time between different gathering modes and flows.

of evacuation time and density. As shown in Figure 7, the average evacuation time under the disorderly distribution is lower than that under the orderly distribution. When there are 35 evacuees with the orderly distribution, it takes 21 seconds to evacuate and is 9.3% higher than that of disorderly distribution. In the entire process of evacuation, partial maximum flow density of orderly distribution reached 1.2/m$^2$; flow density subject to two-thirds of all required time is greater than 1.0/m$^2$; flow density of disorderly distribution is significantly less than that of orderly distribution, with the highest density being 0.92 people/m$^2$ (see Figure 8). The maximum flow density figures of disorderly and orderly gathering modes are shown in Figures 9 and 10. When the number of evacuees is 10 or 15 during evacuation, there are no significant differences for evacuation density of the door and the corridor between two statuses. Once the number of evacuees is over 20, the maximum flow density under orderly distribution in the corridor and door is significantly higher than that of disorderly distribution. Along with increased flow size, the evacuation efficiency of disorderly distribution is higher than that of orderly distribution. Evacuees along the corridor or in each corner can sense and avoid the danger more quickly. Besides, randomly distributed evacuees are less hindered by tables and chairs, which undermine the moving capacity.

*4.2. The Escape Route Choices Based on Different Crowd Gathering Modes and Crowd Size.* Personalized evacuation and spatial utilization rates are shown in Figures 11 and 12. There is obvious aggressive and competitive behavior concerning the choice of main escape routes. Less than 20 persons in the space lead to a smaller space utilization gap under orderly and disorderly state, and the main bottleneck is located at the exit. More than 25 persons lead to the restless state under orderly and disorderly distribution, and the utilization rate of the one-sided corridor is significantly higher than that of the other sided corridor, particularly with centered corridor utilization rate at best. It indicates that

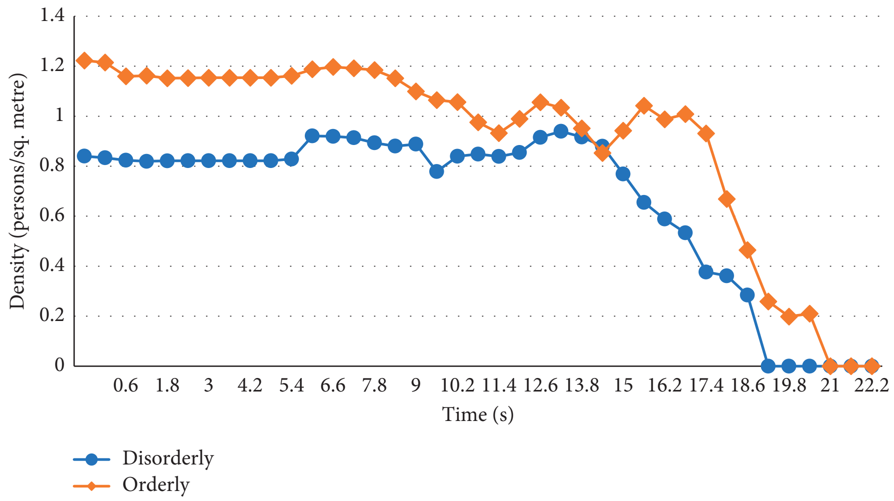
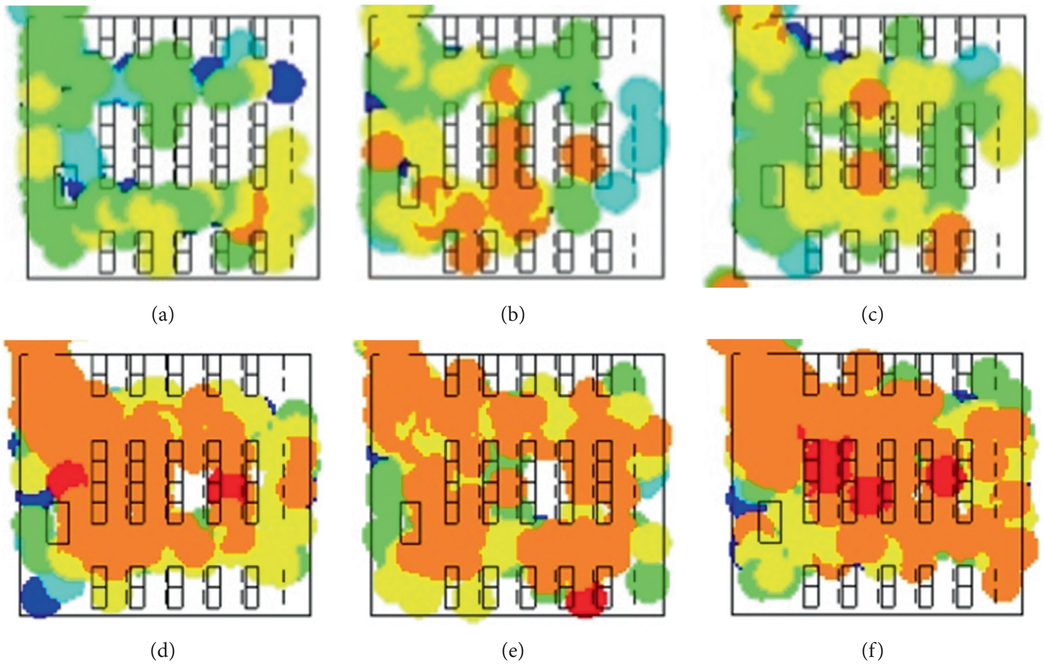


Figure 8: Local maximum density variation in the process of evacuation.


(a) (b) (c)

(d) (e) (f)

Figure 9: Flow size-based cumulative maximum density under disorderly distribution conditions. (a) 10. (b) 15. (c) 20 (d) 25. (e) 30. (f) 35.

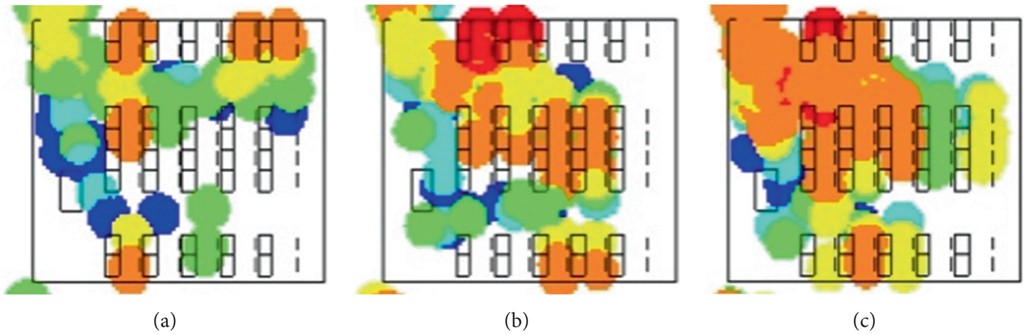
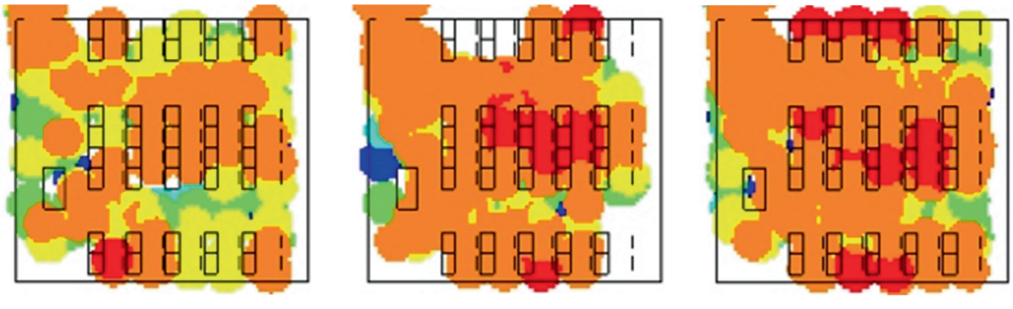
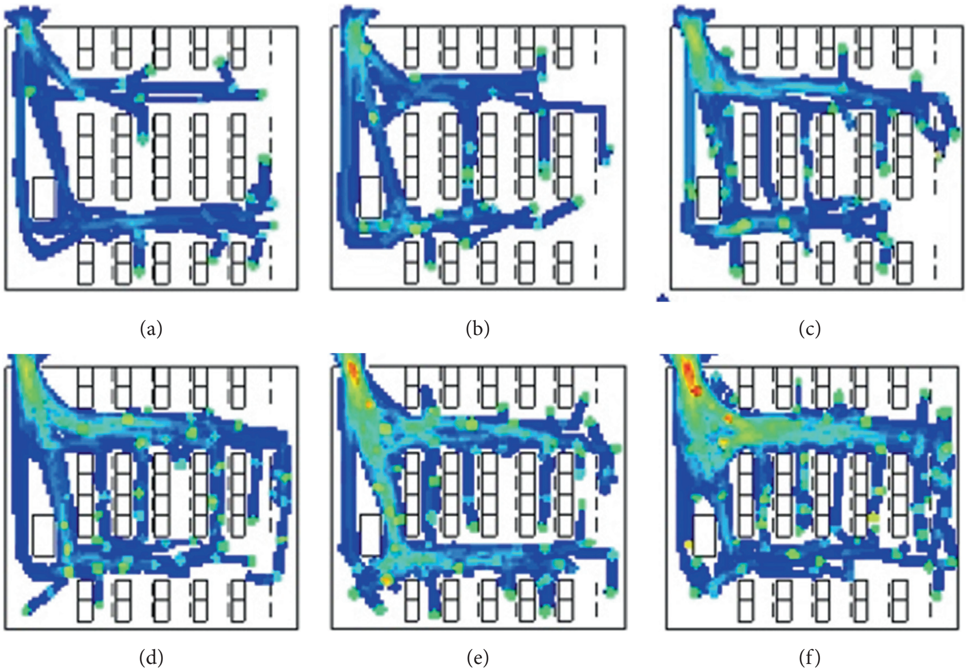

(a) (b) (c)

Figure 10: Continued.



(d) (e) (f)

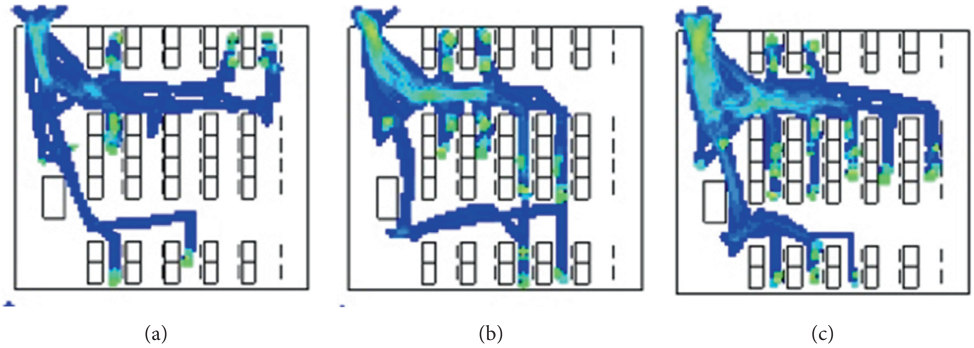
Figure 10: Flow size-based cumulative maximum density under orderly distribution conditions. The space utilization illustrates the space using of pedestrians in an emergency. The more the routes are chosen, the higher the space utilization is, and the deeper the color is. The blue color denotes the less choice, and the red color denotes the more choice. (a) 10. (b) 15. (c) 20 (d) 25. (e) 30. (f) 35.



(a) (b) (c)

(d) (e) (f)

Figure 11: Flow size-based space use rate under disorderly distribution conditions. The space utilization illustrates the space using of pedestrians in an emergency. (a) 10. (b) 15. (c) 20 (d) 25. (e) 30. (f) 35.



(a) (b) (c)

Figure 12: Continued.

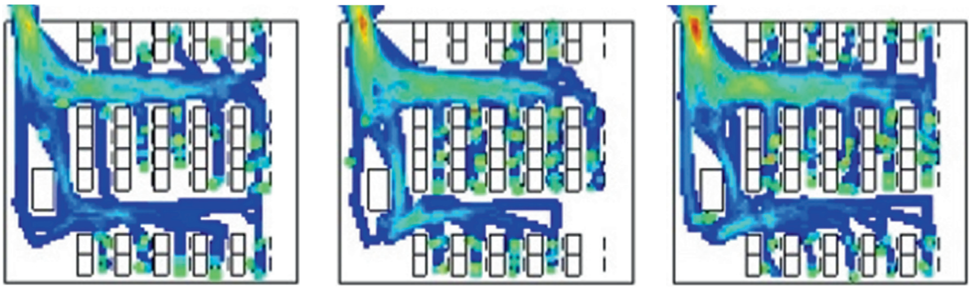


Figure 12: Flow size-based space use ratio under orderly distribution conditions. The space utilization illustrates the space using of pedestrians in an emergency. (a) 10. (b) 15. (c) 20 (d) 25. (e) 30. (f) 35.

evacuees within the limited space tend to occupy the central area, which greatly affects the moving capacity. Evacuees under the orderly distribution quickly leave their seat before flocking to the corridor and the exit (see Figure 12), where evacuees mainly and conveniently occupy under the disorderly distribution, rendering the flow more balanced, and the exit and corridor density is lower than that of orderly distribution.

## 5. Conclusions

The simulation results discussed in this section show that the two considered gathering modes influence the evacuation efficiency in limited space. Our conclusions are as follows.

First of all, the simulation model shows that it benefits evacuees more from initial disorderly distribution than from the orderly distribution as shown from the indicators (i.e., evacuation efficiency). Especially when it comes to more than 25 persons, it leads to the obvious difference between the two distribution conditions.

Moreover, the spatial utilization of the corridor and the exit is better under the disorderly distribution than under the orderly one, and the overall evacuation density is also lower than that under the orderly distribution. Under different circumstances, there are conflicts concerning the choice of escape routes. The exit and the surrounding areas are mostly congested.

Finally, the utilization rate of the central corridor is higher than that of either-sided corridors, which indicates that evacuees within the limited space tend to occupy the central area and this is detrimental to the moving capacity.

In this paper, we study the generally limited building space before launching research on a large sports venue and a railway waiting hall. Findings hereof are of great use for similar research on building facilities layout.

## Data Availability

Data are available in the supplementary materials.

## Additional Points

A safety evacuation model for pedestrians within limited spaces was proposed. It integrates individual behavior into the evaluation model, builds personalized evacuation utility functions based on different factors, and analyzes the evacuation efficiency of different position distribution and flow sizes.

## Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

## Acknowledgments

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## Supplementary Materials

The supplementary materials contain coordinates, velocity, and density data for each simulation entity. (*Supplementary Materials*)

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