Safety Science 124 (2020) 104575

Contents lists available at ScienceDirect

Safety Science

journal homepage: www.elsevier.com/locate/safety

Pedestrian evacuation within limited-space buildings based on different exit design schemes

Zhihong Li[a], Wangtu (Ato) Xu[b,*]

[a] School of Civil and Transportation Engineering, Beijing University of Civil Engineering and Architecture, Beijing 100044, China
[b] Department of Urban Planning, Xiamen University, Xiamen 361005, China

ARTICLE INFO

Keywords:
Traffic safety
Pedestrian evacuation
Limited-space buildings
Cellular automata model
Exit design scheme
Individual utility

ABSTRACT

Considering the differences in the individual characteristics of pedestrians and the influence factors of buildings, we proposed a safety evacuation model for limited spaces. Evacuation efficiency, bottleneck area density, escape route characteristics, and similar factors were analyzed on the basis of different exit widths and operating doors. Results indicated that at an exit width of 1.1 m, the evacuation time was at a low-rising shock steady state with a normal crowd size. Therefore, the exit width of 1.1 m was the most advantageous in terms of evacuation time and construction cost. The aisle center was used more than the sides. The movement of pedestrians to the middle position affected the traffic capacity of the aisle. In comparison with outward-opening doors, inward-opening doors had a definite advantage in terms of evacuation efficiency, area density, and space utilization. When inward-opening doors are used, the escape path is consistent with the exit direction. The aisle width was reduced under the outward-opening door condition, and a bottleneck was formed. The escape route of pedestrians under the outward-opening door condition resembled the letter “Z”. Our experiment did not directly test the behavior in real evacuations but emphasized the role of different designs in real human decision making in a virtual environment. Our findings may be useful in identifying topics for future studies on real human crowd movement, exit design, and facility layout.

1. Introduction

Pedestrian traffic in crowded places, such as transfer hubs, exhibition centers, airports, and so on, must be fully understood. The potential need for the emergency evacuation of facilities due to fires, earthquakes, and other calamities has increased the concern of authorities regarding safe and efficient building design (Haghani and Sarvi, 2016; Bandini et al., 2014; Fridolf et al., 2013). Crowd congestion can have disastrous consequences (Lin et al., 2016; Helbing et al., 2000; Helbing et al., 2007; Fahy et al., 2012), and many crowd disasters can be avoided with enhanced facility design and crowd management (Haghani and Sarvi, 2016). Several studies have investigated these issues in conjunction with building safety (Fridolf et al., 2013; Gershon et al., 2008; Dellolio et al., 2013).

Developing modeling tools and methodologies for predicting pedestrian dynamics during the design stages of buildings and thus preventing such incidents is meaningful (Gwynne et al., 1999; Duives et al., 2013; Roh et al., 2009). Conducting traffic simulations under different possible conditions can enable authorities to improve building safety (Von Sivers et al., 2016). Accordingly, pedestrian simulation and model development are essential in decision making with regard to public safety (Groner, 2016). This significance has led to the development of commercial simulation tools, such as Visswalk, Legion, Anylogic, and Simwalk; however many important aspects of crowd behavior remain poorly understood, particularly under different design schemes and extreme emergency scenarios (Shiwakoti, 2016; Aghabayk et al., 2014). The reliability and accuracy of existing crowd simulation programs for practical design purposes remain limited.

Facility and exit layouts are important in the evacuation of pedestrians from buildings; pedestrians likely compete for security exits and push one another during escape (Vermuyten et al., 2016; Tan et al., 2015; Kang et al., 2015; Gwynne et al., 1999). Any sudden change in the state of a crowd can easily lead to swarming, jostling, and other secondary disasters (Tang et al., 2017; Helbing et al., 2007). A good design scheme can effectively improve evacuation efficiency; on the contrary, poor design may lead to unnecessary harm (Zhu, 2010; Liu et al., 2016).

In this paper, we present a safe evacuation model for pedestrians in limited spaces on the basis of different exit schemes. In a building with limited space, the potential behavioral heterogeneity exhibited by

* Corresponding author.
E-mail address: ato1981@163.com (W.A. Xu).

https://doi.org/10.1016/j.ssci.2019.104575
Received 28 April 2018; Received in revised form 7 July 2019; Accepted 6 December 2019
Available online 30 December 2019

individuals during a certain egress or evacuation scenario adds to the complexity of the problem due to the restriction of evacuation time, space, obstacle layout, and related factors. The proposed model is calibrated by a simulation and applied to real case studies.

2. Literature review

Two factors are critical during the evacuation process, namely, human behavior and building environment. Pioneering work within the recent two decades has been conducted to analyze human behaviors and enhance the safety strategies implemented in crowded spaces (Roh et al., 2009; Bruyelle et al., 2014; Shi et al., 2012). The analysis of evacuation behavior is the key link that ensures evacuation safety, optimizes facility layout, and maintains competent congestion management (Song et al., 2006; Lovreglio et al., 2015; Mu et al., 2013; Chen et al., 2016; Cao et al., 2009). Human escape behavior can be represented in several manners by simulation (Zhou et al., 2016). Previous models simulate evacuees as a continuous homogeneous mass that behaves as a fluid flowing along corridors (Ballerini et al., 2008; Corbetta et al., 2014; Hughes, 2003), considering pedestrian movement and trip-making decisions (Helbing et al., 2007; Groner, 2016; Ronchi et al., 2016). However, these simulation models are not highly accurate in describing pedestrian movement (Ronchi et al., 2016; Gwynne et al., 1999). Human behavior is jointly determined by individual internal cognition and external environment, and evacuation movement can be significantly affected by the interaction between obstacles and humans. Proposing a mathematical model that can predict pedestrian behaviors accurately is difficult. Thus, microscopic models focus on the movement and interaction of individual pedestrians (Helbing et al., 2000; Asano et al., 2011; Kuligowski and Peacock, 2005; Ronchi and Kinsey, 2011). Typical microscopic models include the social force (Zeng et al., 2014; Zanlungo et al., 2011; Helbing and Molnar, 1995), agent-based simulation (Tan et al., 2015; Basak and Gupta, 2017; Wagner and Agrawal, 2014; Joo et al., 2013; D'Orazio et al., 2014), cellular automata (Tao and Dong, 2017; Yu and Song, 2007; Ji et al., 2013; Dihidar and Choudhury, 2004; Lovreglio et al., 2015), multi-grid (Tovbin, 2002; Ma et al., 2002), floor fluid (Jun et al., 2013), and particle (Tang et al., 2017) models. Pedestrians may have different familiarities with buildings and choose their own escape routes that are not necessarily the shortest paths (Li, 2017; Faure and Maury, 2014; Guo and Huang, 2011).

An essential task of building evacuation is representing the inherent link between human behavior and facility design (Tan et al., 2015). Pedestrians' route choice behavior in multi-exit classrooms and channels has been explored (Huang and Guo, 2008; Guo and Huang, 2011; Ma et al., 2017; Lovreglio et al., 2014a). Experimental studies were carried out to analyze the influence of emergency signage and crowded bottleneck area (Fu et al., 2018; Tobias et al., 2006). Fu et al. came to conclusion that both signage detection and acceptance probabilities under individual conditions are larger than those under group situations. S. M. Lo et. al. also have done a lot of research in the field of exit choice (Lo et al., 2006) and pre-evacuation behavior (Liu and Lo, 2011). Individual differences in route choice regarding the dynamic spatial accessibility due to smoke or congestion have also been considered (Bagarello et al., 2015; Nguyen et al., 2013; Hao et al., 2014; Zhou et al., 2017). In addition, the differences in people's spatial knowledge of buildings and analyzed evacuation efficiency were investigated in previous studies (Zhu, 2010; Rogsch et al., 2014; Shi et al., 2012; Li, 2017). Pedestrians may follow self-estimated quickest routes and decide whether to redirect away from danger depending on their physical and psychological characteristics (Li, 2017). This problem has been viewed from different perspectives, such as pedestrian simulation in different facilities (Yu and Song, 2007; Rogsch et al., 2014) and feature analyses of crowd behavior in complex maneuvers (Helbing et al., 2000; Moussaid et al., 2011; Aghabayk et al., 2014). The major reasons for this approach are the scarcity of dedicated empirical data and lack of cohesion of different industries, thereby hindering the validation and calibration of existing models (Zhou et al., 2017; Wahlqvist and van Hees, 2016; Ronchi et al., 2016; Busogi et al., 2017). A few studies have partially addressed the lack of explanatory data by providing choice data, conducting experimental studies in relatively simple geometries, and monitoring actual pedestrian movements in large crowds (Lovreglio et al., 2014a; Lovreglio et al., 2016b; Lovreglio et al., 2016a; Lovreglio et al., 2014b; Li, 2017; Guo and Huang, 2011).

The spatial accessibility of buildings can vary due to uncertain conditions or overcrowding, and individualized route choices related to the pedestrian awareness of predictable changes have not been fully described. Studies on the exit designs of buildings remain in the exploratory stage, and pedestrian behaviors substantially vary under different schemes. This difference directly affects evacuation efficiency. A synthesis of relevant studies and existing specifications reveals that the group and individual behaviors of evacuating crowds have not been further explored, and research on route choice utility and behavior is also inadequate. In the present study, a safe evacuation model for pedestrians in limited spaces is established, and a simulation analysis is performed by analyzing evacuation efficiency, bottleneck density, and the route decision making of pedestrians in different schemes under various exit design conditions.

3. Experimental setting

3.1. Experimental setting of different exit widths

Relevant architectural design codes are continuously improving, and salient provisions are now present for the numbers of people and exits for individual buildings. However, no clear conclusion has been established regarding the exit width that improves the evacuation efficiency of crowds. This study uses the exit settings of small existing classrooms and explores the best exit size under the most effective evacuation conditions on the basis of present building patterns. The evacuation exits of small and medium classrooms of current domestic schools are mostly in front, and the doors have widths of 0.8–1.2 m. To investigate the effect of evacuation exit size on evacuation efficiency while considering the placement of classroom seats and without reducing the numbers of desks and chairs, the maximum door width can be set to 1.9 m. In the experiment, the door width is analyzed and set as 0.8, 0.9, …, 1.8, and 1.9 m (Fig. 1).

3.2. Experimental setting for different door-opening patterns

The common door-opening patterns of current building spaces are inward and outward; doors in civil buildings open inward, and those at stair exits open outward. The inward opening makes the door closest to the wall because the door type and wall angle do not match. Field

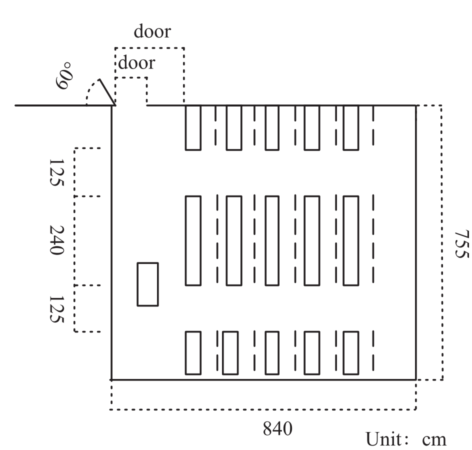

Fig. 1. Doors of different widths (0.8, 0.9, …, 1.9 m) in a room.

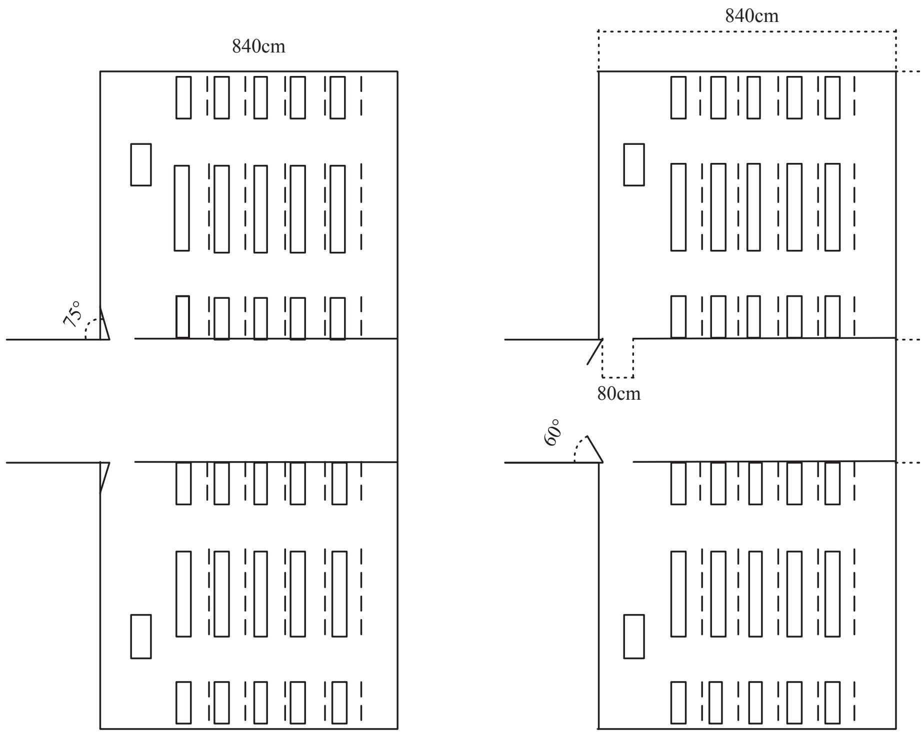

Fig. 2. Scene settings of different door-opening designs.

investigations reveal that the angles of the inward- and outward-opening doors of a selected building are approximately 75° and 60°, respectively (see Fig. 2).

4. Models

4.1. Basic rules

The model scene uses a 2D plane. Each cell has the general size of 40cm × 40cm; its state is either occupied or vacant. A cell can be a wall, facility, or pedestrian, and an exit cell is set in a limited space. Pedestrians can leave only from the exit, and each cell has eight neighborhoods for options. In each simulation step, pedestrians can move to adjacent cells or stay in their original cells (Fig. 3).

$$(x, y) = \begin{cases} 1 & occupied \quad cel \\ 0 & occupied \quad cel \end{cases} \tag{1}$$

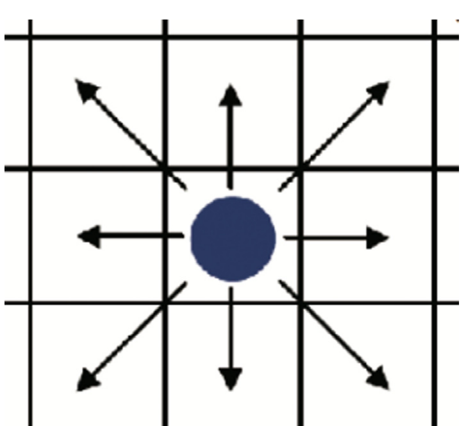

Fig. 3. Movement rules and probability distribution.

$$F(x, y) = \{(m, n)||m - x| \leq 1, |n - y| \leq 1, \quad (m, n) \in \Omega^2\} \tag{2}$$

Each cell in $F(x, y)$ has two states, namely, direction parameter $D(i, j)$ and vacant parameter $E(i, j)$. Therefore, a 3 × 3 matrix, such as $F(x, y)$, can be represented by $D(i, j)$ and $E(i, j)$. $Pr(i, j)$ is the transition probability of the direction that may be selected by pedestrians and determined by the direction and vacant parameters.

$$Pr(i, j) = D(i, j) + E(i, j) \tag{3}$$

$$D(i, j) = \frac{L(x, y) - L(m, n)}{\sqrt{(m - x)^2 + (n - y)^2}} \tag{4}$$

$$E(i, j) = \begin{cases} \max(D(i, j)), (m, n) = 0, \\ 0, \quad m = x, n = y \\ -\max(D(i, j)), \quad (m, n) = 1, (m, n) \neq (x, y) \end{cases} \tag{5}$$

Here, $L(x, y)$ is the optimal effect estimated between $Cell(i, j)$ and the exit.

4.2. Individual escape utility function of pedestrians

The impedance judgment of sections varies in the evacuation of pedestrians in limited spaces. Several pedestrians may judge the front section differently because of their varying characteristics. The calculation of $L(x, y)$ involves several factors, and this work considers three factors, namely, the relative service level, obstacle resistance, and physical characteristic factors. With the assumption of a linear relationship between the three factors and the optimal utility (Eq. (6)), a nonlinear relationship can also be used in practice.

$$L(x, y) = \sum_k c_k L_k(x, y), \tag{6}$$

where $L_k(x, y)$ represents the utility value of different path attributes k, and c_k represents the relevant weight or importance of each factor. Not all weight coefficients in the model are uniquely determined by the observation. The relative importance among the weights is the only relevant coefficient. c_k is related to the group of pedestrians, and different groups have varying destinations and c_k.

(1) Service level factor

Pedestrians consider the service level factor of the front path when selecting paths during an evacuation. This factor involves the number of pedestrians and the degree of crowding toward front access. The degree of crowding is mainly related to pedestrian density and access speed.

$$L_1(x, y) = \frac{\rho_L}{\rho_A}, \tag{7}$$

where ρ_L is the average density centered on pedestrian i in the current small area, and ρ_A is the average density of pedestrians in the adjacent front area. The greater the difference in density between the front and adjacent areas, the larger the crowding index.

(2) Obstacle resistance factor

The obstacle in the model area is presented as $O_m \subset \Omega,\ m = 1,\ \cdots, M$. For any obstacle within a certain distance0 $FixDis$, the distance from the running costl_2 and pedestrians to the obstacle is a monotonically decreasing function. Such distance also has a monotonically increasing function with the angle between the pedestrian movement direction and the obstacle gradient. If the value exceeds the limit, then the obstacles are deemed to have no effect on the escape of pedestrians. Fig. 4 illustrates that when the distance is close to 50 m, the effect of the obstacles on people is 0, and when the angle is 0°, the effect of the wall on the pedestrians is also 0.

$$L_2(x, y) = \omega_1 g_m(d(O_m, x)) + \omega_2 h_m(Angle(O_m, \theta)) \tag{8}$$

$$L_2(x, y) = \omega_1 a_m \exp(-\frac{d(O_m, x)}{b_m}) + \omega_2 \frac{Angle^2}{90^2} \tag{9}$$

$$d(O_m, x) = {}^{\min}_{y \in O_m}\{\|x - y\|\} \tag{10}$$

The distance $d(O_m, x)$between pedestrians and the obstacle is the shortest, and $\|x - y\|$ refers to the module of vector $x - y$. $a_m > 0$ and $b_m > 0$ are model parameters that describe the affected area of the obstacle, and their values depend on the type of obstacle, such as walls, trees, and newsstands. c_2 is the weight that reflects the pressure of the obstacle, which largely depends on its type. $Angle(O_m, \theta)$ is the angle between the forward direction of pedestrians and the obstacle, and the scope is $Angle \in [0, 90^{\circ}]$. If the effect of $Angle$ on pedestrians is assumed as a quadratic function with a nonlinear relationship, that is, (1) when the forward direction θ of pedestrians is parallel to obstacle $O_m$and the effect on them is 0 and expressed as $h_m(Angle(O_m, \theta)) = 0$, and (2) when the forward direction θ of pedestrians is perpendicular to obstacle O_m and the effect on them is 1 and expressed as $h_m(Angle(O_m, \theta)) = 1$, then

$$h_m(Angle(O_m, \theta)) = \frac{1}{90^2} Angle^2 \tag{11}$$

(3) Physical characteristic factor

The escape speed of pedestrians $||v||$ is related to their age and physical strength. $||v||$ is a balance between the time of escape and the energy consumed to maintain a certain speed. The energy of pedestrians is also related to their age. The physical characteristic factor is defined as follows:

$$L_3(x, y) = \frac{1}{2}\ ||v||^2 f(Age) \tag{12}$$

where $f(Age)$ indicates that the relationship between the energy and age of pedestrians can be expressed as the relationship between their age and free flow rate. The collected speed of pedestrians in a 50×8 shuttle run is calibrated as follows:

$$f(Age) = \begin{cases} -0.03Age^2 + 0.5993Age + 3.4388 & Gender = male \\ -0.0226Age^2 + 0.389Age + 3.7214 & Gender = female \end{cases} \tag{13}$$

Based on previous factors, the individual section utility function of pedestrians during an emergency is the following.

$$L(x, y) = c_1 \frac{\rho_L}{\rho_A} + c_2 \left[\omega_1 a_m \exp(-\frac{d(O_m, x)}{b_m}) + \omega_2 \frac{Angle^2}{90^2}\right] + c_3 \frac{1}{2}\ ||v||^2 f(Age) \tag{14}$$

The calibration of c_1, c_2, and c_3 in the function can be set on the basis of actual needs. If pedestrians are primarily concerned about the

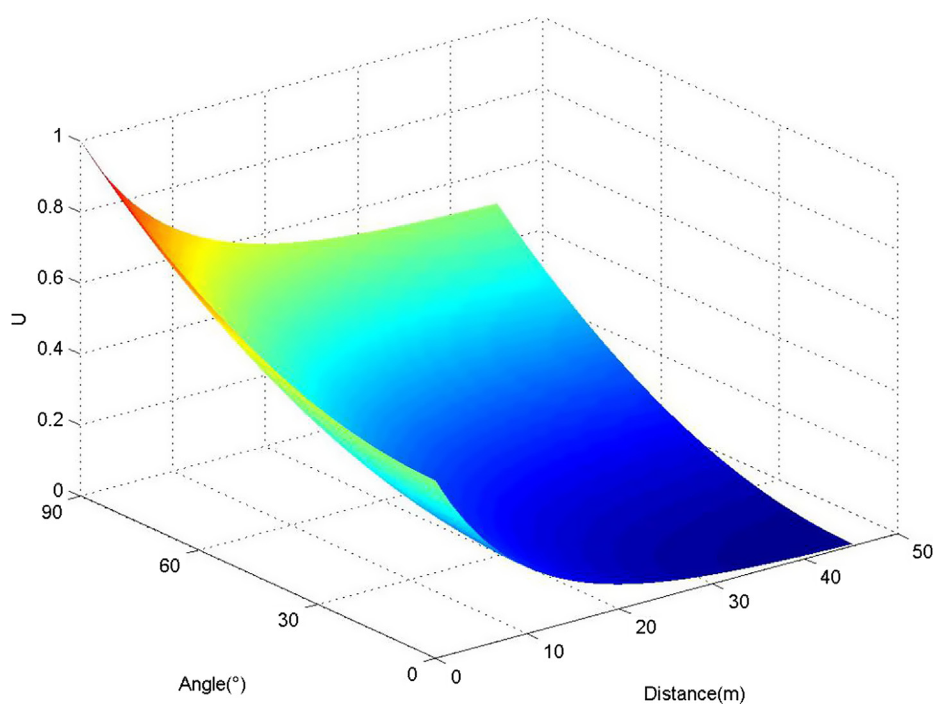

Fig. 4. Influences of angle and obstacle distance.

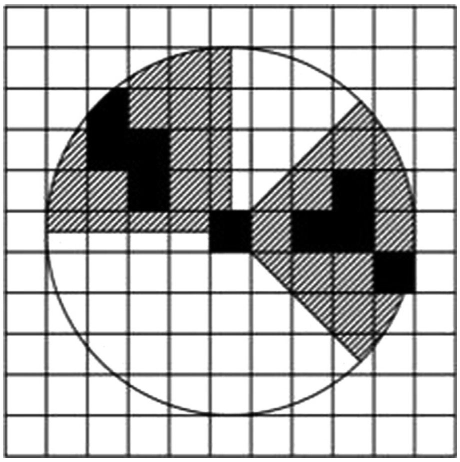

Fig. 5. Feasible movement direction and calibration of vision fields.

service level, then the coefficients can be set as {0.5, 0.3, 0, 2}. Other calibrations can be performed in the same manner.

4.3. Setting of visual area and feasible movement direction

According to the rules of the movement direction of cells, cellular visual fields are defined as V_{ij}^k, $k = 1, 2, \cdots, 8$, which represents eight directions that span clockwise from the east (Fig. 5). For example, V_{ij}^1 is the number of cells that are not occupied by $Cell(i, j)$ in the east visual field. "Visual field" refers to the area that pedestrians can see from their location. For example, the east visual field mainly includes 12 cells and occupies four cells; therefore, $V_{ij}^1 = 8$. Similarly, the northwest direction includes 13 major cells and occupies four cells; thus, $V_{ij}^7 = 9$.

At each time, the probability that the $Cell(i \pm 1, j \pm 1)$ is not occupied by the pedestrian along the eight directions is calculated as follows. If the entity moves east, then the cell is $Cell(i + 1, j)$.

$$PV_{ij}^k = \exp\left[\omega_S S_{i,j} + \omega_D D_{i,j} + \omega_V V_{i,j}^k + \sum_{m \in k}\left(\omega_C C_r^m + \frac{\omega_E}{E_{i,j}^m}\right)\right](1 - \mu_{i,j})\xi_{i,j} \tag{15}$$

$$P_{ij}^k = PV_{ij}^k / \sum_{\forall k} PV_{ij}^k,\ k = 1, 2, \cdots, 8 \tag{16}$$

S_{ij} and D_{ij} are the static and dynamic ranges of$Cell(i, j)$, respectively. The corresponding weight coefficients are ω_S and ω_D. Coefficient ω_D denotes the proportion trend of the conformity; the greater the value, the stronger the effect of flocking. Static range S_{ij} of the cell is not affected by time and pedestrians and can be calculated as follows:

$$S_{ij} = min_{i_{Ts}, j_{Ts}}\{max_{i_h, j_h}\{\sqrt{(i_{Ts} - i_h)^2 + (j_{Ts} - j_h)^2}\} - \sqrt{(i_{Ts} - i)^2 + (j_{Ts} - j)^2}\} \tag{17}$$

Here, (i_h, j_h) refers to the maximum values in all distance ranges to Cell (i_{Ts}, j_{Ts}). D_{ij} is the dynamic value of$Cell(i, j)$, which is updated with the simulated step size, and the initial value is 0. When people move from $Cell(i, j)$ to the neighboring cell, 1 is added to the D_{ij} of $Cell(i, j)$, that is, $D_{ij} = D_{ij} + 1$. If D_{ij} is not increased in the succeeding step size time, then it is reduced until it becomes 0, that is, $D_{ij} = D_{ij}(1 - \alpha)$. C_r^m is the capacity of exit m in unit time and is defined as the number of cells available in the affected area of radius r in unit time; ω_C is its corresponding sensitivity parameter, and $E_{i,j}^m$ is the Euclidean distance. $\mu_{i,j} = 0$ if the cell is occupied.

On the basis of this model, a simulation analysis of different scenarios is conducted. Pedestrians compete for the exit and the main access. When several people enter the same cell simultaneously, it is distributed according to the optimal principle of the same direction; that is, the closer the forward direction to the cell, the greater the probability of occupation.

5. Results

5.1. Simulation results and discussions of different exit widths

A simulation analysis is performed in this study on the basis of different exit widths. Twelve programs are present, in which building spaces with the same layout but different exit widths are considered. Pedestrian characteristics differ, and the optimal utility function $L(x, y)$ calculated on the basis of the model varies, resulting in differences in individual evacuation path selection. Therefore, a rational and optimal exit width can effectively improve evacuation efficiency and decrease construction cost.

5.1.1. Evacuation efficiency and strength analysis of different exit width schemes

The comparison result of different exit widths is presented in Fig. 6. In the initial stage of the simulation, the overall evacuation time decreases as exit width increases. When the door is wider than 1.1 m, the evacuation time only slightly fluctuates as exit width increases and remains stable. When the exit width is 1.1 m, the evacuation efficiency and resource utilization are balanced well in the limited space. From the aspect of evacuation density, when the exit width is different, the crowding of noticeably varying degrees occurs in different positions. Fig. 7 illustrates that when the exit widths are 0.8 and 0.9 m, evident crowding occurs at the exit location; the maximum density reaches 1.44 people/m^2. No serious crowding is observed at the exit location in schemes in which the exit is wider than 1.0 m; the maximum exit density is approximately 0.75 people/m^2. Different from the conclusion

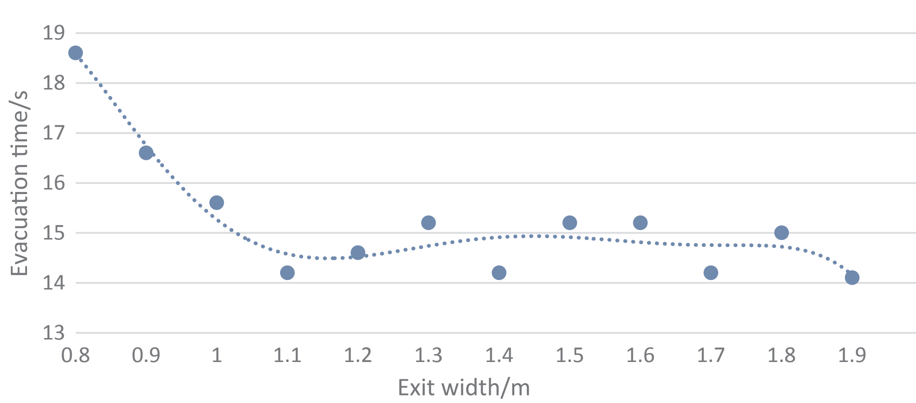

Fig. 6. Comparison of escape times of all schemes.

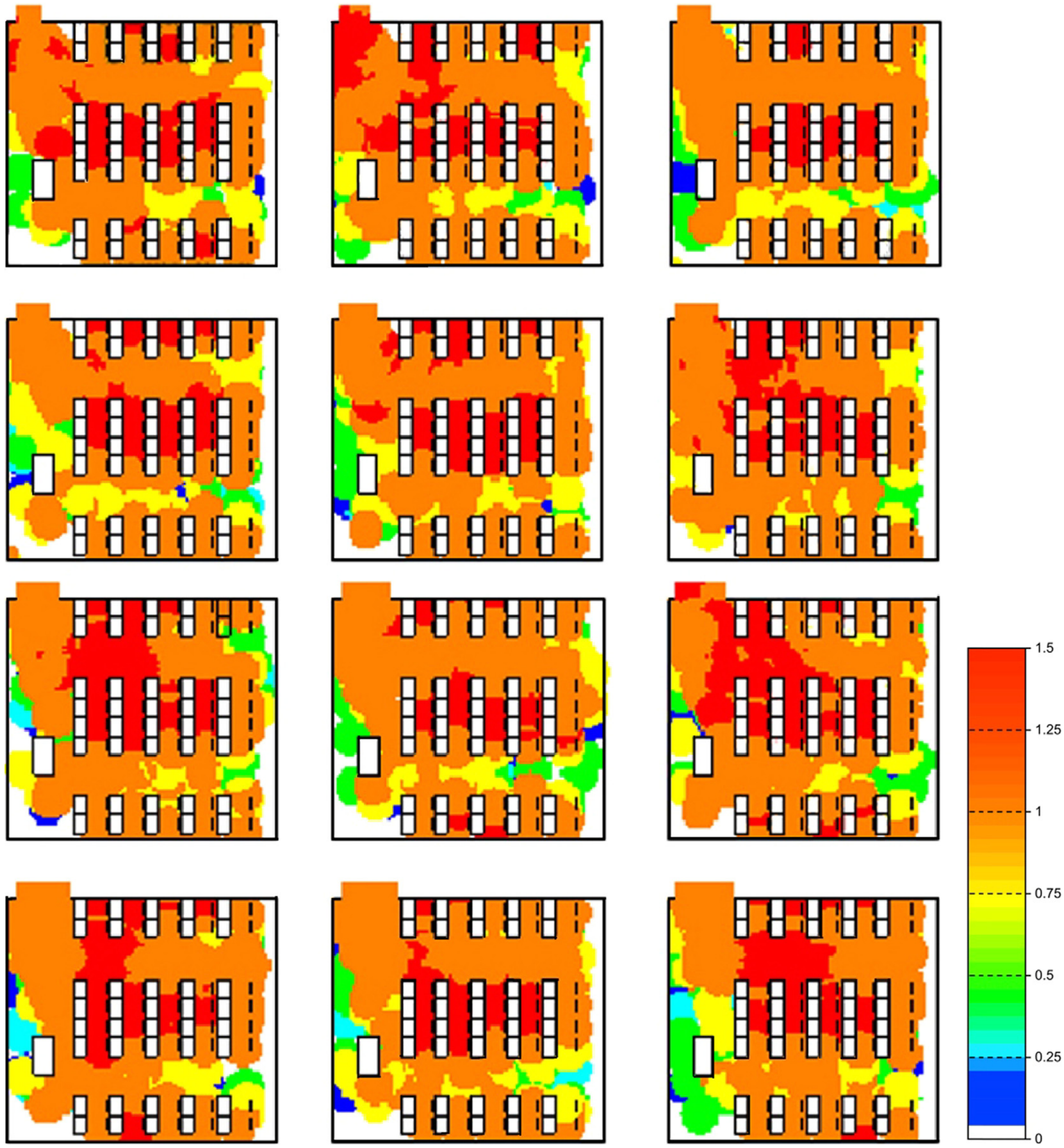

Fig. 7. Cumulative maximum densities of all schemes.

that a wide exit leads to reduced crowding in normal situations, the maximum density of the exit population is at its lowest when the exit widths are 1.0, 1.1, 1.8, and 1.9 m, and evacuation efficiency is at its highest. When the exit widths are 1.1, 1.7, and 1.9 m, evacuation efficiency is at its highest and the population density at the exit is at its lowest. Evacuation efficiency is at its lowest at exit widths of 0.8, 0.9, and 1.6 m; the exit area is crowded, especially when the width is 0.9 m.

5.1.2. Evacuation route choice and space utilization of different exit width schemes

During the evacuation process, the route choice is similar (Figs. 8 and 9), and the competition for the exit and the main access is evident. Crowding mainly occurs in the exit location and the passage near the exit. When the exit is narrow, a bottleneck is formed near the exit, and the population density of the bottleneck area is more than 1.3 people/m^2. When the exit is wider than 1.4 m, the bottleneck effect at the exit location disappears, and the passage near the exit becomes the largest bottleneck, but the overall evacuation efficiency improves. When the exit width is between 0.8 and 1.4 m, the difference in space utilization is small. When the exit is wider than 1.4 m, space utilization is low, and no apparent bottleneck occurs. Some people cross the seat during an evacuation, and the utilization of the passage along the side near the door is significantly higher than that along the other side of the passage. The space utilization of the center of the passage is higher than that of both sides. This finding indicates that pedestrians likely occupy the middle of the passage when escaping limited passages by group, thereby affecting the capacity of the passage.

5.2. Effect of evacuation exit door on evacuation behavior

In the same building space, different door-opening designs lead to various bottleneck characteristics, resulting in variations between individual evacuation path selection and space occupancy situation. Therefore, a reasonable door-opening design can effectively improve evacuation efficiency and reduce unnecessary capacity loss.

5.2.1. Evacuation efficiency and strength of different manners of door opening

A simulation analysis is conducted on the basis of the different manners of door opening, and two programs are considered. The overall evacuation time of the simulation (Table 1) reveals that evacuation efficiency with the inward-opening door is higher than that with the outward-opening door. The cumulative maximum density of the doorway area with the outward-opening door is higher than that with

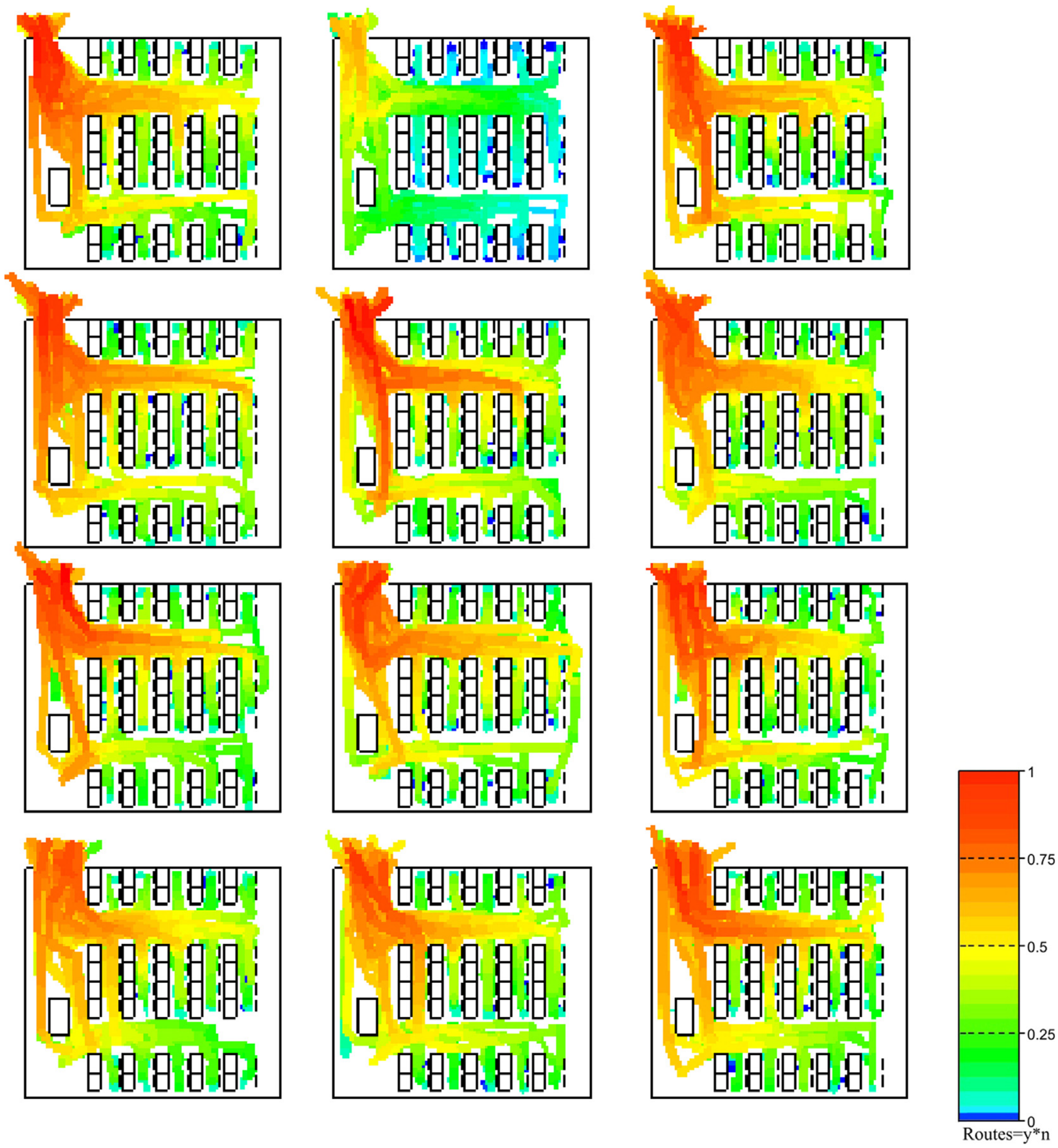

Fig. 8. Escape routes of all schemes. These escape routes illustrate the route choices of pedestrians. The more routes are selected, the deeper the color. The green color denotes less choice, whereas the red color denotes more choice. The number of routes ranges from 0% to 100% of the number of people. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the inward-opening door. The main reason for these findings is that the space occupied by the inward-opening door is 0.15 m^2 and does not affect the capacity of the passage. With the outward-opening door, the space inside the door is not affected, but the passage width outside the door is reduced from 3.5 m to 2.1 m due to the opening of the door. In addition, the capacity of the passage is reduced by 40% (the right-hand side of Fig. 10), thereby forming a bottleneck at the door-opening location. This bottleneck affects crowd evacuation inside the door and substantially increases the population densities inside and outside the door.

5.2.2. Escape route choice and space utilization of different manners of door opening

The simulation results indicate a considerable difference between the evacuation path and spatial utilization of the two schemes (Figs. 11 and 12). The escape path of pedestrians with the inward-opening door is always consistent with the main direction. With the outward-opening door, several pedestrians exhibit a Z-shaped large-angle roundabout reentry path and follow other invalid escape paths due to the influence of the passage width. The most congested points in the space utilization with the inward-opening door are concentrated in the middle of the door, and the crowd gradually turns toward this location, in which the space utilization and population density are at their highest. The highest space utilization with the outward-opening door also appears in the middle of the door, but the steering angle is small, and the space utilization of the passage is high due to the effect of the door. Consequently, a bottleneck point appears.

6. Discussion

In this research, various assumptions and factors are used to determine the evacuation time, evacuation efficiency, and resource utilization. Several studies are related to the current work in at least one aspect. These studies exceed what is reported in the following, but the focus is on the parts that are comparable to this experiment. For example, (Helbing et al., 2003) reported the results of an evacuation exercise of a classroom. Several researchers found that the capacity increases with the exit width under single-exit conditions. The greater the total width and the more emergency exits are present, the lower the total capacity (Wang et al., 2014; Hao et al., 2014). Pursals and Garzon

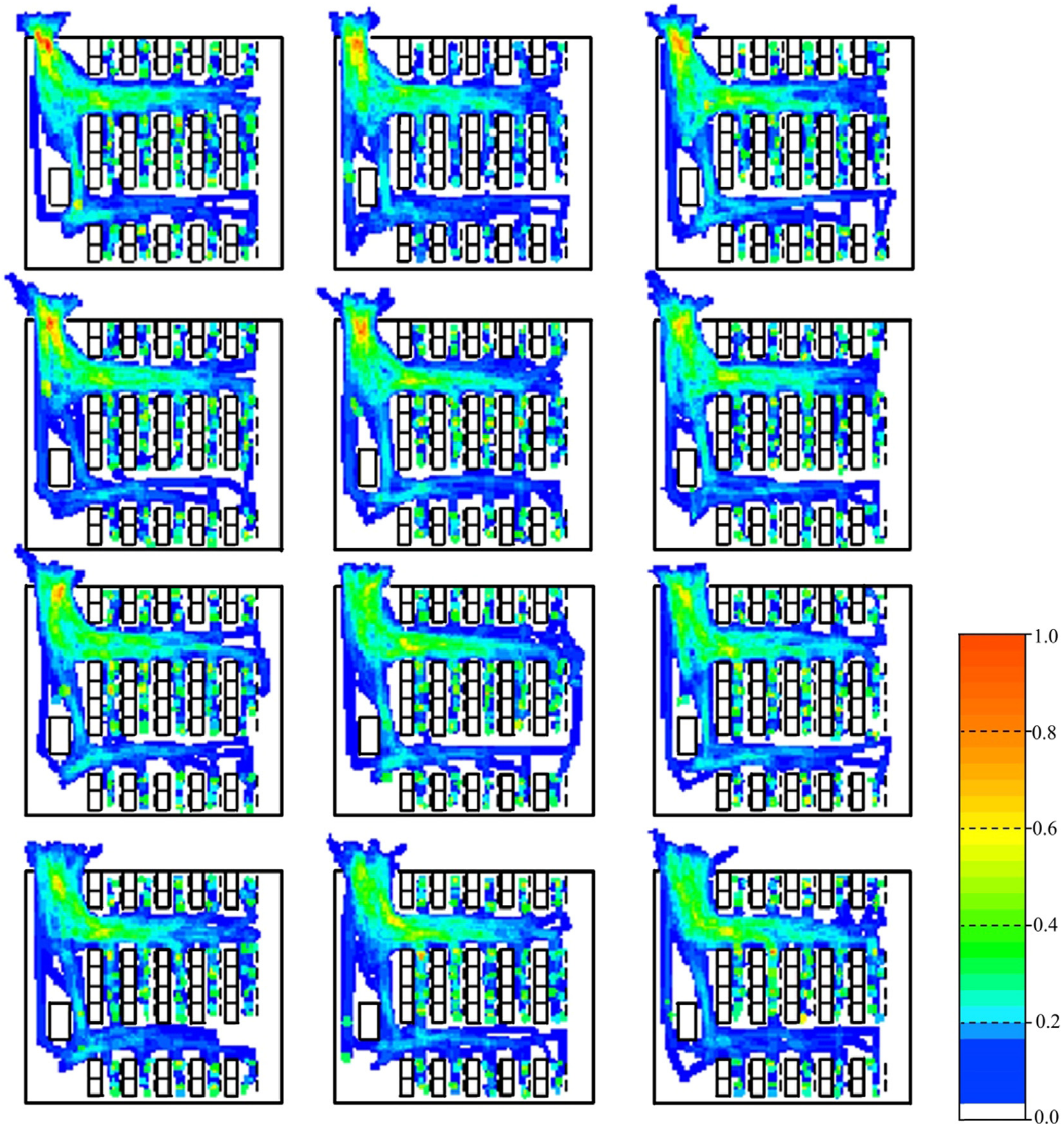

Fig. 9. Space utilization of all schemes. Space utilization illustrates how pedestrians use space during an emergency. Space utilization ranges from 0% to 100%. The more routes are chosen, the higher the space utilization, and the deeper the color. The blue color denotes less choice, whereas the red color denotes more choice. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Simulation time of all schemes.

Door opening	Inward door opening	Outward door opening
Evacuation time	24 s	26 s

(2009) incorporated exit widths and access areas to enable their model to address congestion caused by limited door capacity. Bode et al. (2015) revealed that participants can base their exit choices on time-dependent information, such as differences in queue lengths and speeds at exits, rather than time-independent information, such as differences in exit widths or route lengths. Certain researchers have introduced a decision support system for determining a safe and short (in terms of time and distance) evacuation path and for increasing situational awareness during emergencies in large critical infrastructures (Pursals and Garzon, 2009; Guo and Huang, 2011).

Certain discrepancies have also been observed in the experiment. Evacuation efficiency and resource utilization reach a good balance in limited spaces. In normal situations, the maximum density of the exit population is at its lowest, and evacuation efficiency is at its highest when the exit widths are 1.0, 1.1, 1.8, and 1.9 m. During evacuation, the route choice is similar, and evident competition for the exit and the main access is observed. Pedestrians likely occupy the middle of the limited passage. In addition, different manners of door opening form various bottleneck characteristics in the same building space, resulting in variations between individual evacuation route choice and space occupancy.

7. Conclusion

To simulate the evacuation process in buildings with limited spaces, the individual optimal effect of the evacuated population is calculated on the basis of a safe evacuation model for pedestrians in limited spaces under different exit schemes. The effect of the exit width and door opening in buildings is also analyzed. The main conclusions are as follows:

(1) When the exit width of a building is set and a normal evacuation population is considered, evacuation time is not reduced with any further increase in exit width after it reaches 1.1 m. However, a small fluctuation is observed. Therefore, the exit width is set at 1.1 m, which is the optimal point for evacuation time and

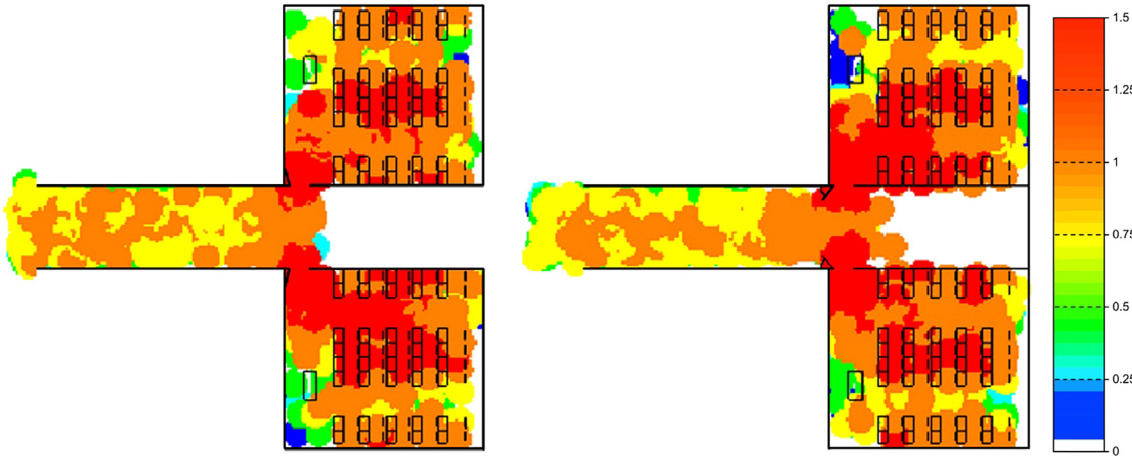

Fig. 10. Cumulative maximum densities of different door-opening designs.

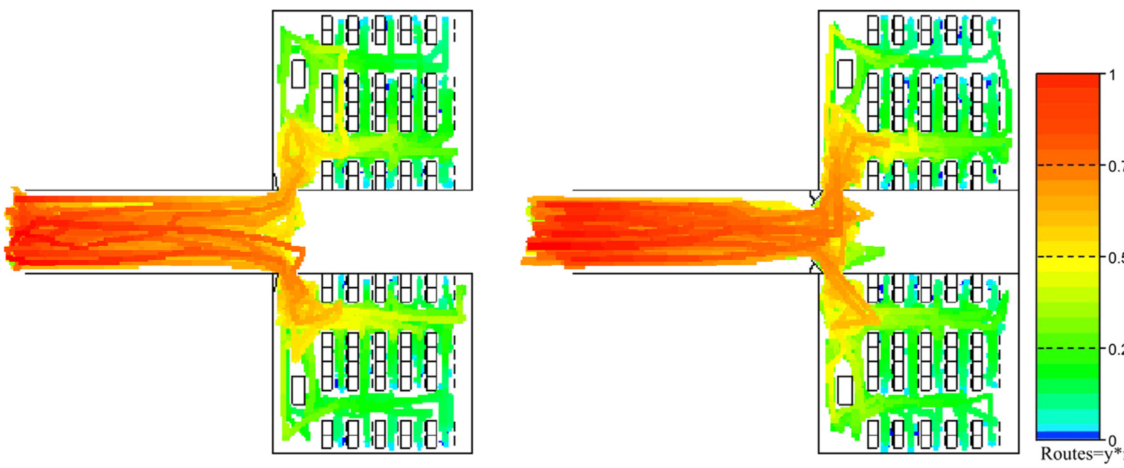

Fig. 11. Escape routes with different door-opening designs. These escape routes illustrate the route choices of pedestrians. The more routes are chosen, the deeper the color. The green color denotes less choice, whereas the red color denotes more choice. The number of routes ranges from 0% to 100% of the number of people. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

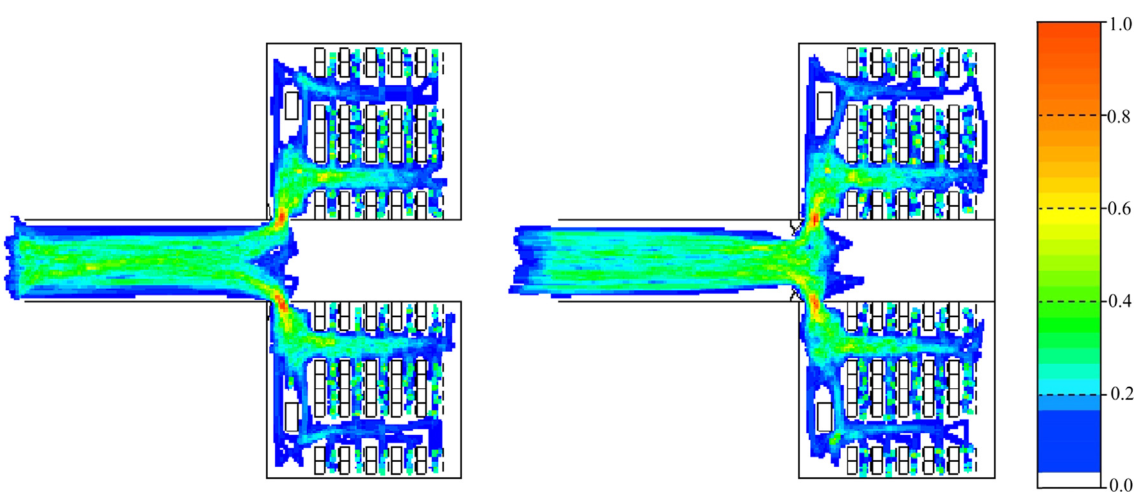

Fig. 12. Space utilization with different door-opening designs. Space utilization illustrates how pedestrians use space during an emergency. Space utilization ranges from 0 to 100%. The more routes are chosen, the higher the space utilization, and the deeper the color. The blue color denotes less choice, whereas the red color denotes more choice. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

construction cost. As exit width increases, population density at the exit location decreases. Different from the conclusion that a wide exit leads to reduced crowding in normal situations when the exit widths are 1.0, 1.1, 1.8, and 1.9 m, the exit crowd and average densities are at their lowest and the evacuation efficiency is at its highest.

(2) Under different exit width conditions, pedestrians compete for the exit and the main access. Crowding mainly appears at the exit

location and the passage near the exit. Bottlenecks form near narrow exits. When the exit width exceeds 1.4 m, the bottleneck effect at the exit location disappears, and the passage near the exit becomes the largest bottleneck.

(3) Compared with the outward-opening door, the inward-opening door is significantly dominant in evacuation efficiency, doorway area density, and space utilization. With the inward-opening door, the escape path of pedestrians is consistent with the main direction. With the outward-opening door, the limited passage width is reduced, and an apparent bottleneck forms at the door location, thereby affecting the crowd evacuation inside the door. In addition, certain pedestrians follow a Z-shaped large-angle roundabout reentry path, and the population densities inside and outside the door are increased.

(4) The spatial utilization rate of the center of the passage during an evacuation is higher than that of the two sides. Therefore, pedestrians likely occupy the middle of the limited passage, thereby affecting the capacity of the entire passage.

The construction space investigated in this study is small, thus a follow-up evacuation efficiency analysis of facility layout, exit location, and widths of comprehensive transportation hubs and sports fields will be conducted in future research. Our results provide support for the layout designs and exit widths of buildings.

Acknowledgements

This work has been supported in part by Program of Beijing Advanced Innovation Center for Future Urban Design with Beijing University of Civil Engineering and Architecture: “Analysis of passenger decision-making behavior and Research on facility optimization design of transport hub based on deep learning (No. 2019-14)”.

References

Aghabayk, Kayvan, Ejtemai, Omid, Sarvi, Majid, Sobhani, Amir, 2014. Understanding pedestrian crowd merging behavior. Transp. Res. Procedia 2, 768–773.
Asano, Youichi, Saito, Tatsuhiko, Ito, Yoshihiro, Shiomi, Katsuhiko, Hirose, Hitoshi, Matsumoto, Takumi, Aoi, Shin, Hori, Sadaki, Sekiguchi, Shoji, 2011. 'Spatial distribution and focal mechanisms of aftershocks of the 2011 off the Pacific coast of Tohoku Earthquake'. Earth Planets Space 63, 29.
Bagarello, Fabio, Gargano, Francesco, Oliveri, Francesco, 2015. A phenomenological operator description of dynamics of crowds: escape strategies. Appl. Math. Model. 39, 2276–2294.
Ballerini, M., Cabibbo, N., Candelier, R., Cavagna, A., Cisbani, Evaristo, Giardina, Irene, Lecomte, V., Orlandi, A., Greg Parisi, A., Procaccini, A., Viale, Massimiliano, Zdravkovic, V., 2008. Interaction Ruling Animal Collective Behaviour Depends on Topological rather than Metric Distance: Evidence from a Field Study.
Bandini, Stefania, Mondini, Matteo, Vizzari, Giuseppe, 2014. Modelling negative interactions among pedestrians in high density situations. Transp. Res. Part C: Emerg. Technol. 40, 251–270.
Basak, Biswanath, Gupta, Sumana, 2017. Developing an agent-based model for pilgrim evacuation using visual intelligence: a case study of Ratha Yatra at Puri. Comput. Environ. Urban Syst. 64, 118–131.
Bode, Nikolai W.F., Holl, Stefan, Mehner, Wolfgang, Seyfried, Armin, 2015. Disentangling the impact of social groups on response times and movement dynamics in evacuations. PLoS One 10 (3), e0121227.
Bruyelle, Jeanluc, Neill, Conor O, Elkoursi, Elmiloudi, Hamelin, Fabrice, Sartori, Nicolo, Khoudour, Louahdi, 2014. Improving the resilience of metro vehicle and passengers for an effective emergency response to terrorist attacks. Saf. Sci. 62, 37–45.
Busogi, Moise, Shin, Dongmin, Ryu, Hokyoung, Yeong Gwang, Oh., Kim, Namhun, 2017. Weighted affordance-based agent modeling and simulation in emergency evacuation. Saf. Sci. 96, 209–227.
Cao, X.B., Xu, Y.W., Chen, D., Qiao, H., 2009. Associated evolution of a support vector machine-based classifier for pedestrian detection. Inf. Sci. 179, 1070–1077.
Chen, Yanxiang, Zhang, Luming, Liu, Xiao, Chen, Chun, 2016. Pedestrian detection by learning a mixture mask model and its implementation. Inf. Sci. 372, 148–161.
Corbetta, Alessandro, Bruno, Luca, Muntean, Adrian, Toschi, Federico, 2014. High statistics measurements of pedestrian dynamics. Transp. Res. Procedia 2, 96–104.
D'Orazio, Marco, Spalazzi, Luca, Quagliarini, Enrico, Bernardini, Gabriele, 2014. Agent-based model for earthquake pedestrians' evacuation in urban outdoor scenarios: Behavioural patterns definition and evacuation paths choice. Saf. Sci. 62, 450–465.
Dellolio, Luigi, Ibeas, Angel, Barreda, Rosa, Sanudo, Roberto, 2013. Passenger behavior in trains during emergency situations. J. Saf. Res. 46, 157–166.
Dihidar, Kajal, Choudhury, Pabitra Pal, 2004. Matrix algebraic formulae concerning some exceptional rules of two-dimensional cellular automata. Inf. Sci. 165, 91–101.
Duives, Dorine C., Daamen, Winnie, Hoogendoorn, Serge P., 2013. State-of-the-art crowd motion simulation models. Transp. Res. Part C: Emerg. Technol. 37, 193–209.
Fahy, Rita, Proulx, Guylène, Aiman, Lata¸ 2012. Panic or not in fire: Clarifying the misconception.
Faure, Sylvain, Maury, Bertrand, 2014. Crowd motion from the granular standpoint. Math. Models Methods Appl. Sci. 25, 463–493.
Fridolf, Karl, Nilsson, Daniel, Frantzich, Hakan, 2013. Fire evacuation in underground transportation systems: a review of accidents and empirical research. Fire Technol. 49, 451–475.
Fu, Libi, Cao, Shuchao, Song, W.G., Fang, Jie¸ 2018. The influence of emergency signage on building evacuation behavior: An experimental study.
Gershon, Robyn R M, Pearson, Julie M, Nandi, Vijay, Vlahov, David, Bucciarelliprann, Angela, Tracy, Melissa, Tardiff, Kenneth, Galea, Sandro, 2008. Epidemiology of subway-related fatalities in New York City, 1990–2003. J. Saf. Res. 39, 583–588.
Groner, Norman E., 2016. A decision model for recommending which building occupants should move where during fire emergencies. Fire Saf. J. 80, 20–29.
Guo, Ren Yong, Huang, Hai Jun, 2011. Route choice in pedestrian evacuation: formulated using a potential field. J. Stat. Mech: Theory Exp. 2011, P04018.
Gwynne, S., Galea, E.R., Owen, M., Lawrence, P.J., Filippidis, L., 1999. A review of the methodologies used in the computer simulation of evacuation from the built environment. Build. Environ. 34, 741–749.
Mu, H.L., Wang, J.H., Mao, Z.L., Sun, J.H., Lo, S.M., Wang, Q.S., 2013. Pre-evacuation human reactions in fires: an attribution analysis considering psychological process. Procedia Eng. 52, 290–296.
Haghani, Milad, Sarvi, Majid, 2016. Human exit choice in crowded built environments: Investigating underlying behavioural differences between normal egress and emergency evacuations. Fire Saf. J. 85, 1–9.
Hao, Yue, Shuai, Wang, Lei, Zhang, Shao, Chunfu, 2014. Setting method of emergency exits in pedestrian walking facilities. J. Beijing Jiaotong Univ. 38, 1–6.
Helbing, Dirk, Farkas, Illes J, Vicsek, Tamas, 2000. Simulating dynamical features of escape panic. Nature 407, 487–490.
Helbing, Dirk, Isobe, Motonari, Nagatani, Takashi, Takimoto, Kouhei, 2003. Lattice gas simulation of experimentally studied evacuation dynamics. Phys. Rev. E 67, 067101.
Helbing, Dirk, Johansson, Anders, Alabideen, Habib Z, 2007. Dynamics of crowd disasters: an empirical study. Phys. Rev. E 75, 046109–46209.
Helbing, Dirk, Molnar, Peter, 1995. Social force model for pedestrian dynamics. Phys. Rev. E 51, 4282–4286.
Huang, Haijun, Guo, Renyong, 2008. Static floor field and exit choice for pedestrian evacuation in rooms with internal obstacles and multiple exits. Phys. Rev. E 78, 021131–21231.
Hughes, Roger L., 2003. The flow of human crowds. Annu. Rev. Fluid Mech. 35, 169–182.
Ji, Xiangfeng, Zhang, Jian, Ran, Bin, 2013. A study on pedestrian choice between stairway and escalator in the transfer station based on floor field cellular automata. Phys. A Stat. Mech. Appl. 392, 5089–5100.
Joo, Jaekoo, Kim, Namhun, Wysk, Richard A., Rothrock, Ling, Son, Young-Jun, Yeonggwang, Oh., Lee, Seungho, 2013. Agent-based simulation of affordance-based human behaviors in emergency evacuation. Simul. Model. Pract. Theory 32, 99–115.
Jun, Yang, Zhongsheng, H.O.U., Minghui, Zhan, 2013. Simulation of pedestrian dynamic using a vector floor field model. Int. J. Modern Phys. C 24, 1240.
Kang, Jihyun, Jeong, In-Jae, Kwun, Joon-Bum, 2015. Optimal facility–final exit assignment algorithm for building complex evacuation. Comput. Ind. Eng. 85, 169–176.
Kuligowski, Erica, Peacock, Richard D., 2005. A Review of Building Evacuation Models.
Li, Zhihong, 2017. An emergency exits choice preference model based on characteristics of individual diversity. Adv. Mech. Eng. 9,4(2017-4-01) 9: 168781401769354.
Lin, Peng, Ma, Jian, Liu, Tianyang, Ran, Tong, Si, Youliang, Li, Tao, 2016. An experimental study of the “faster-is-slower” effect using mice under panic. Phys. A: Stat. Mech. Appl. 452, 157–166.
Liu, M., Lo, S.M., 2011. The quantitative investigation on people's pre-evacuation behavior under fire. Autom. Constr. 20, 620–628.
Liu, Yu., Shi, Yi, Jiang, Tao, Liu, Jian-Zhou, Wang, Wei-Jie, 2016. Metamodel-based direction guidance system optimization for improving efficiency of aircraft emergency evacuation. Comput. Ind. Eng. 91, 302–314.
Lo, S.M., Huang, H.C., Wang, P., Yuen, K.K., 2006. A game theory based exit selection model for evacuation. Fire Saf. J. 41, 364–369.
Lovreglio, R., Fonzone, A., dell'Olio, L., Borri, D., Ibeas, A., 2014a. The role of herding behaviour in exit choice during evacuation. Procedia Soc. Behav. Sci. 160, 390–399.
Lovreglio, Ruggiero, Borri, Dino, dell'Olio, Luigi, Ibeas, Angel, 2014b. A discrete choice model based on random utilities for exit choice in emergency evacuations. Saf. Sci. 62, 418–426.
Lovreglio, Ruggiero, Fonzone, Achille, dell'Olio, Luigi, 2016a. A mixed logit model for predicting exit choice during building evacuations. Transp. Res. Part A: Policy Pract. 92, 59–75.
Lovreglio, Ruggiero, Fonzone, Achille, dell'Olio, Luigi, Borri, Dino, 2016b. A study of herding behaviour in exit choice during emergencies based on random utility theory. Saf. Sci. 82, 421–431.
Lovreglio, Ruggiero, Ronchi, Enrico, Nilsson, Daniel, 2015. Calibrating floor field cellular automaton models for pedestrian dynamics by using likelihood function optimization. Phys. A: Stat. Mech. Appl. 438, 308–320.
Ma, Y.G., Wang, K., Wei, Y.B., Ma, G.L., Cai, X.Z., Chen, J.G., Fang, D.Q., Guo, W., Shen, W.Q., Tian, W.D., 2002. Isoscaling in the lattice gas model. Phys. Rev. C 69, 051601.
Ma, Yaping, Li, Lihua, Zhang, Hui, Chen, Tao, 2017. Experimental study on small group behavior and crowd dynamics in a tall office building evacuation. Phys. A: Stat. Mech. Appl. 473, 488–500.
Moussaid, Mehdi, Helbing, Dirk, Theraulaz, Guy, 2011. How simple rules determine pedestrian behavior and crowd disasters. PNAS 108, 6884–6888.

Nguyen, Manh Hung, Ho, Tuong Vinh, Zucker, Jean-Daniel, 2013. Integration of Smoke Effect and Blind Evacuation Strategy (SEBES) within fire evacuation simulation. Simul. Model. Pract. Theory 36, 44–59.
Pursals, S.C., Garzon, F.G., 2009. Optimal building evacuation time considering evacuation routes. Eur. J. Oper. Res. 198, 305–314.
Rogsch, Christian, Galster, Ralf, Luthardt, Thomas, Mohr, Daniel, 2014. The effect of pedestrian placement and pre-movement times on evacuation simulation. Transp. Res. Procedia 2, 291–299.
Roh, Jae Seong, Ryou, Hong Sun, Park, Won Hee, Jang, Yong Jun, 2009. CFD simulation and assessment of life safety in a subway train fire. Tunn. Undergr. Space Technol. 24, 447–453.
Ronchi, Enrico, Kinsey, Michael¸ 2011. Evacuation models of the future: insights from an online survey of user's experiences and needs.
Ronchi, Enrico, Reneke, Paul A., Peacock, Richard D., 2016. A conceptual fatigue-motivation model to represent pedestrian movement during stair evacuation. Appl. Math. Model. 40, 4380–4396.
Shi, Congling, Zhong, Maohua, Nong, Xingzhong, He, Li, Shi, Jiehong, Feng, Guoguan, 2012. Modeling and safety strategy of passenger evacuation in a metro station in China. Saf. Sci. 50, 1319–1332.
Shiwakoti, Nirajan, 2016. Understanding differences in emergency escape and experimental pedestrian crowd egress through quantitative comparison. Int. J. Disaster Risk Reduct. 20, 129–137.
Song, Weiguo, Xuan, Xu., Wang, Binghong, Ni, Shunjiang, 2006. Simulation of evacuation processes using a multi-grid model for pedestrian dynamics. Phys. A Stat. Mech. Appl. 363, 492–500.
Tan, Lu., Mingyuan, Hu., Lin, Hui, 2015. Agent-based simulation of building evacuation: combining human behavior with predictable spatial accessibility in a fire emergency. Inf. Sci. 295, 53–66.
Tang, Biwei, Zhu, Zhanxia, Shin, Hyo-Sang, Tsourdos, Antonios, Luo, Jianjun, 2017. A framework for multi-objective optimisation based on a new self-adaptive particle swarm optimisation algorithm. Inf. Sci. 420, 364–385.
Tao, Y.Z., Dong, L.Y., 2017. A Cellular Automaton model for pedestrian counterflow with swapping. Phys. A: Stat. Mech. Appl. 475, 155–168.
Tobias, Kretz, Anna, Grünebohm, Michael, Schreckenberg, 2006. Experimental study of pedestrian flow through a bottleneck. J. Stat. Mech: Theory Exp. 2006, P10014.
Tovbin, Yu.K., 2002. Lattice-gas model in equilibrium, kinetic and dynamic problems of adsorption. Appl. Surf. Sci. 196, 71–80.
Vermuyten, Hendrik, Beliën, Jeroen, De Boeck, Liesje, Reniers, Genserik, Wauters, Tony, 2016. A review of optimisation models for pedestrian evacuation and design problems. Saf. Sci. 87, 167–178.
Von Sivers, I., Templeton, A., Künzner, F., Köster, G., Drury, J., Philippides, A., Neckel, T., Bungartz, H.J., 2016. Modelling social identification and helping in evacuation simulation. Saf. Sci. 89, 288–300.
Wagner, Neal, Agrawal, Vikas, 2014. An agent-based simulation system for concert venue crowd evacuation modeling in the presence of a fire disaster. Expert Syst. Appl. 41, 2807–2815.
Wahlqvist, Jonathan, van Hees, Patrick, 2016. Implementation and validation of an environmental feedback pool fire model based on oxygen depletion and radiative feedback in FDS. Fire Saf. J. 85, 35–49.
Wang, Shuai, Yue, Hao, Zhang, Binya, Li, Juan, 2014. Setting the width of emergency exit in pedestrian walking facilities. Procedia Soc. Behav. Sci. 138, 233–240.
Yu, Y.F., Song, Weiguo, 2007. Cellular automaton simulation of pedestrian counter flow considering the surrounding environment. Phys. Rev. E 75, 046112.
Zanlungo, Francesco, Ikeda, Tetsushi, Kanda, Takayuki, 2011. Social force model with explicit collision prediction. EPL 93, 68005.
Zeng, Weiliang, Chen, Peng, Nakamura, Hideki, Iryoasano, Miho, 2014. Application of social force model to pedestrian behavior analysis at signalized crosswalk. Transp. Res. Part C Emerg. Technol. 40, 143–159.
Zhou, Min, Dong, Hairong, Wang, Fei-Yue, Wang, Qianling, Yang, Xiaoxia, 2016. Modeling and simulation of pedestrian dynamical behavior based on a fuzzy logic approach. Inf. Sci. 360, 112–130.
Zhou, Zhuping, Cai, Yifei, Ke, Ruimin, Yang, Jiwei, 2017. A collision avoidance model for two-pedestrian groups: considering random avoidance patterns. Phys. A: Stat. Mech. Appl. 475, 142–154.
Zhu, Kong Jin, 2010. The effects of exit position and internal layout of classroom on evacuation efficiency. Acta Phys. Sinica 59, 7701–7707.