Modeling, simulation and analysis of the evacuation process on stairs in a multi-floor classroom building of a primary school

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Modeling, simulation and analysis of the evacuation process on stairs in a multi-floor classroom building of a primary school

Wenhang Li [a,b], Yi Li [c], Ping Yu [d], Jianhua Gong [a,b,*], Shen Shen [a,b], Lin Huang [a,b], Jianming Liang [a,b]

[a] *State Key Laboratory of Remote Sensing Science, Institute of Remote Sensing and Digital Earth, Chinese Academy of Science, Beijing, China*

[b] *Zhejiang & CAS Application Center for Geoinformatics, Zhejiang, China*

[c] *State Key Laboratory of Cotton Biology, Institute of Cotton Research, Chinese Academy of Agricultural Sciences, Henan, China*

[d] *School of Management, Xinxiang University, Henan, China*

HIGHLIGHTS

- A stair-unit model was proposed to depict the topologies of a stairwell.
- The simulated process was compared with a real evacuation drill.
- Qualitative and quantitative consistencies were achieved.
- Congestion is one of the main reasons for the increase in evacuation time on stairs.
- A preferred layout is one where a building has classrooms with the same grade.

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ABSTRACT

Few studies have focused on the evacuation of multi-floor classroom buildings in a primary school, a process that differs from evacuations in other buildings. A stair-unit model was proposed to describe the spatial topology of twisting stairwells and to describe the spatial relationship between stairwells and floors. Based on the stair-unit model, a schedule-line model was proposed to calculate evacuation paths in stair-units; a modified algorithm to calculate pedestrian forces were proposed to describe the evacuee movements in stairwells; and a projection strategy was proposed to model the 3-dimensional evacuation process in multi-floor buildings. The simulated processes were compared with a real evacuation drill. The results showed that the simulated process achieved qualitative and quantitative consistencies with the real drill, proving the appropriateness of the proposed models and algorithms. Based on the validation, further simulations were conducted and a few rules for evacuations in stairwells were identified including rules governing the impact of the moment of entering a staircase, the number of students in a class, the stagger strategy, and the layout of grades on different floors on the time in stairwell and the total evacuation duration. The results can be used to mitigate the effects of a fire disaster, and

* Correspondence to: State Key Laboratory of Remote Sensing Science, Institute of Remote Sensing and Digital Earth, Chinese Academy of Science, Beijing, 100101, China.

E-mail address: gongjh@radi.ac.cn (J. Gong).

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the proposed models and algorithms can also be referenced by evacuation simulation for other multi-floor buildings such as residential buildings.

1. Introduction

In modern cities, the scarcity of land resources and the growing number of residents has led to the construction of multi-floor buildings that typically hold a large number of people [1]. In emergency situations such as fires, people need to be removed from the building, and emergency evacuation is therefore a major concern of building designers, building occupants and governments [2–5].

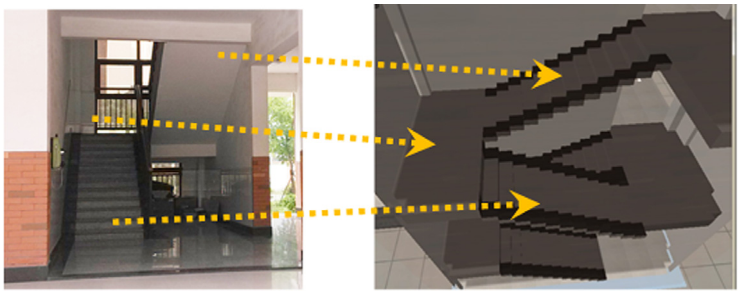
During a fire, the elevators of a multi-floor building are shut down for the sake of safety, leaving stairwells as the only means of escape. It is therefore important to understand evacuation behavior and the evacuation process in stairwells for the safety of residents [6]. Staircase evacuation has been a special subject in the category of human evacuation [7]. Previous studies can be classified into 3 types as follows:

(1) Observation studies. In these studies, pedestrians were not deliberately selected; thus, there was no influence on their behavior, and their natural interactions were preserved. Such studies typically focus on non-emergency behavior or the daily behavior of individuals in stairwells. Qu et al. [8] observed a single-story staircase in a subway station to understand the flow characteristics. They noted that pedestrians walked downstairs faster than upstairs; in addition, the lane-forming phenomenon and sub-group behavior were observed. Because the pedestrian flows were typical daily flows and thus largely unobstructed, little congestion occurred during the observations. In addition, Kretz [9], Fujiyama and Tyler [10], and Yang et al. [7] obtained different results for average walking speed on a staircase under different scenarios.

(2) Experimental studies or evacuation drills. In this approach, a number of pedestrians are selected and forced to evacuate a real building due to a fictitious or simulated disaster, and the motion parameters of a pedestrian and the statistical group features are captured on video for later analysis. However, such an approach requires a large number of pedestrians, and it is time-consuming to organize; thus, it is difficult to repeat the process to test the impact of different parameters on the evacuation due to the limitations of pedestrian stamina and cost. Lei et al. [11] conducted an evacuation drill in a dormitory. The influence of exit and stair conditions on human evacuation was studied. They found that when the exit width is small, the overall flow rate is stable. However, with an increase in width, a significant stratification phenomenon is found in the flow rate. Yang et al. [7] also carried out an experimental study of pedestrian flow on staircases in a dormitory building. They took into account both the building structure and the behavior of student movement. A number of interesting characteristics of staircase movement such as queuing behavior at landings and subgroup behavior were observed. They also found discrepancies between normal and emergency conditions. People move about twice as fast in emergencies than in normal conditions, and the rate of movement in high density areas in emergencies is greater than the rate in low density areas.

(3) Simulation approach. In such an approach, the evacuation process and the physical behavior of pedestrians are mathematically modeled; and a great deal of evacuees with different physical parameters are simulated and driven by the models to evacuate a virtual building. The advantages of such approaches are that the motion data of every simulated evacuee and the pedestrian flow at any moment can be collected for analysis; moreover, real pedestrians and real buildings are not necessary, and limitations of time and space do not come into play. Therefore, the evacuation can be conducted repeatedly to study the impact of each factor as needed. However, the mathematical models, the simulated evacuation process, and the results should be validated before their application, so a real drill or an experiment is always conducted as a comparison and as a means to validate the models [6,8,12]. Xu et al. [6] proposed an improved multi-grid model for staircase evacuations by using a finer discretization of space and by introducing many pedestrian movement factors including rectangular body size, various walking speeds in different densities, and pedestrian turning behavior. Based on a simulation in a student apartment, the authors found that bottlenecks in staircase evacuations exist at locations where students entering from the hallway and students descending from the upper staircase meet with each other, as this leads to congestion in the buffer area, which slows the speed of the crowd down. Qu et al. [8] modified the social force model, focusing on pedestrian movement and evacuation dynamics on stairs by introducing the influence of staircase geometry, the restriction of the step size and the optimal velocity selection. Based on a validation with empirical data in a subway station, they argued that the improved model can obtain individual velocity under different staircase geometries and flow characteristics of the evacuation dynamics. Koo et al. [12] considered the impacts of disabilities on evacuation from high-rise office buildings using a simulation approach based on the BUMMPEE (Bottom-up Modeling of Mass Pedestrian flows—implications for the Effective Egress of individuals with disabilities) model. Two population scenarios, homogeneous (i.e., only residents without disabilities) and heterogeneous residents (i.e., residents with and without disabilities) were analyzed. The authors found that residents with disabilities significantly delay the evacuation process by causing congestion and the blocking phenomenon, and the impacts become more significant as the population size increases.

Because the simulation approach is the focus of this paper, the main problems in previous studies are analyzed here. First, although much progress has been made in evacuation modeling on stairs, previous studies mainly focused on modeling or



(a) A typical twisting stairwell in a real school.

(b) The perspective view of the twisting stairwell.

Fig. 1. A typical twisting stairwell in a real school.

optimizing evacuees' movements by incorporating more factors, and little attention was paid to modeling the structure and in particular the spatial relationship of stairwells and floors. However, in stair evacuations, the physical structures of stairwells determine the boundary of an evacuee's behavior, and the spatial relationships between stairwells and floors further influence or change the behavior of an evacuee. Therefore, it is important and necessary to model the structure and the spatial relationships of stairwells and floors, based on which the behaviors of evacuees and the evacuation processes in multi-floor stairwells can be optimized.

Second, previous studies have rarely addressed the evacuation of a multi-floor classroom building on stairs, in particular in a primary school, which has specific characteristics: (1) Students are assembled and organized in a classroom, and different classes are distributed on different floors. The number of students in a class is usually more than 20, particularly in China. Therefore, the organization of the evacuees is different from that in other buildings, for example, residential buildings; (2) the stairwells in classroom buildings are usually twisting [6]. Here, it should be noted that other buildings such as public commercial buildings and transportation junctions may also be equipped with twisting stairwells; however, twisting stairwells are still one of the major features of multi-floor classroom buildings. (3) although classroom buildings in primary schools are typically multi-floor, they are not very tall and are usually no higher than 3 stories, so the impact of fatigue [2, 4] is slight and can be neglected.

The above differences indicate the characteristics of the evacuation of a multi-floor classroom building, which is the focus of this paper. This paper is organized as follows: in Section 2, the evacuation environment, the evacuee activities, and the evacuation process on stairs were modeled based on the social force model; in Section 3, the evacuation of a 3-floor classroom building was simulated, and qualitative and quantitative comparisons with a real drill were carried out to validate the proposed models; in Section 4, further simulations and analysis were performed to reveal further tendencies in stairwell evacuations in multi-floor classroom buildings.

2. Modeling evacuation process on stairs

2.1. Stair-unit model

When a fire disaster occurs, the elevator is shut down for the sake of safety, and the stairwell, which links different floors, is the main passage and in many cases the only means of escape. In multi-floor classroom buildings, different floors are linked by stairwells, and the spatial connectivity and accessibility from one floor to another are thus built up; at the same time, the spatial relationship of stairwells and that of stairwells and floors influence the evacuee flows and further impact the spatial distributions and mutual influences, i.e., the spatial relationship of different evacuee flows between stairwells and floors. Therefore, it is of great significance to model the physical structures of a stairwell and the spatial relationship between different parts of the stairwell and spatial relationship between the stairwell and floors. Moreover, the stairwell in a classroom building is typically twisting, as shown in Fig. 1, particularly in primary schools in China. The structure of a twisting stairwell is special: the structures of different parts are similar to each other; in other words, a twisting stairwell has the feature of repeatability. Here, a stair-unit model was proposed to describe the structural topologies and the spatial relationships of a part of a twisting stairwell.

As shown in Fig. 2, a stair-unit is composed of 3 segments, an upper surface (P_u), a middle surface (P_m), and a bottom surface (P_b). Among these surfaces, P_u and P_b are inclined, and P_m is horizontal. The topologies between a stair-unit, a stairwell, and floors can be constructed as follows (Fig. 3): (1) A few stair-units form a stairwell, and a stair-unit therefore links with an upper stair-unit (S_u) and a lower stair-unit (S_b); (2) each stair-unit links 2 floors: P_u links with an upper floor (F_u), and P_b links with a lower floor (F_b). The floors F_u and F_b thus connect with each other by the stair-unit, and evacuees can evacuate from F_u to F_b. (3) S_u connects with F_u, and the spatial relationship between S_u and F_u is such that S_u is the upper stair-unit of F_u and F_u is the lower floor of S_u; likewise, S_b connects with F_b, and the spatial relationship between S_b and F_b is

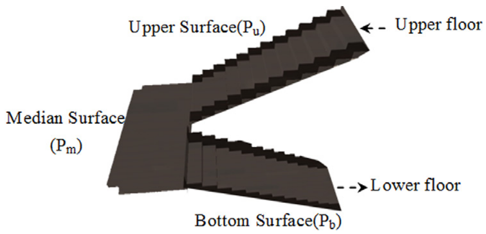


Fig. 2. The stair-unit model.

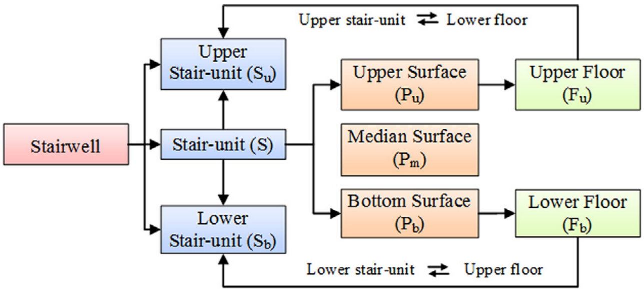


Fig. 3. The spatial topology between stair-units and floors.

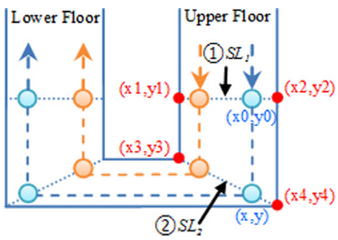


Fig. 4. The schedule-line model.

such that S_b is the lower stair-unit of F_b and F_b is the upper floor of S_b. In this way, the spatial topologies between stair-units and floors can be built up.

2.2. A schedule-line model for evacuee path determination on stairs

Because the social force model [13–19] can better describe the interactions between individuals and can qualitatively reproduce certain self-organizing phenomena such as lane formation and arching, the social force model was employed as the base model to help simulate such evacuation processes. The classical social force model is given as Eqs. (1), (2), and (3). In Eq. (1), the first element on the right side of the equation is the self-driving force from a target. The second element represents the social forces from other pedestrians, in other words, the pedestrian forces (given in Eq. (2)). The third element represents the repulsive forces from the obstacles (given in Eq. (3)). A, B, K, κ are empirical parameters.

$$m_i \frac{\mathrm{d}v_i}{\mathrm{d}t} = m_i \frac{v_i^0(t)e_i^0(t) - v_i(t)}{\tau_i} + \sum_{j(\neq i)} f_{ij} + \sum_{w} f_{iw} \tag{1}$$

$$\mathbf{f}_{ij} = \left\{A_i \exp[(r_{ij} - d_{ij})/B_i] + kg(r_{ij} - d_{ij})\right\} \mathbf{n}_{ij} + \kappa g(r_{ij} - d_{ij}) \Delta v_{ji}^t \mathbf{t}_{ij} \tag{2}$$

$$\mathbf{f}_{iw} = \{A_i \exp[(r_i - d_{iw})/B_i] + kg(r_i - d_{iw})\} \mathbf{n}_{iw} - \kappa g(r_i - d_{iw})(\mathbf{v}_i \cdot \mathbf{t}_{iw})\mathbf{t}_{iw}. \tag{3}$$

Previous studies have argued that in very crowded situations, evacuees always move straight ahead according to their current location rather than making an attempt to move left or right or overtake the pedestrians in front of them [7,8]. From the perspective of the social force model, the target determination of an evacuee in a crowded stair-unit is special. Here, based on the stair-unit model, a schedule-line model is proposed to describe such activities.

In Fig. 4, an evacuee P has reached schedule-line SL_1. The current position is (x_0, y_0), and the next schedule-line is SL_2. SL_1 is defined by a start point (x_1, y_1) and end point (x_2, y_2). SL_2 is defined by a start point (x_3, y_3) and end point (x_4, y_4). Because the edges of a stair are parallel, the next node (x, y) on SL_2 can be obtained according to the similarity theorem (Eq. (4)). In this way, the node series in the stair-unit can be obtained, and the sequential combination of node series in different

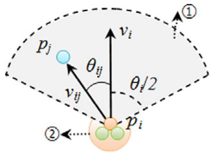


Fig. 5. The modified definition of a pedestrian force range.

stair-units forms the path of evacuee P in the stairwell; in terms of the social force model, these nodes are assigned as targets (Eq. (1)) and exert self-driving forces on evacuee P and guide P to shift between the regions in these stair-units.

$$\begin{cases} x = \dfrac{x_0 - x_1}{x_2 - x_1} \cdot (x_4 - x_3) + x_3 \\ y = \dfrac{y_0 - y_1}{y_2 - y_1} \cdot (y_4 - y_3) + y_3. \end{cases} \tag{4}$$

2.3. A modified pedestrian force model on stairs

Forces between pedestrians are one of the critical drivers of pedestrian behavior. Before calculation of such forces, it is first necessary to determine the neighbors who exert social forces on the target pedestrian. In an emergency evacuation on stairs, evacuees are typically crowded, and an evacuee may be affected by not only the evacuees who are in the view region (Fig. 5①) but also those who are out of the view region but have physical contact with the source evacuee (Fig. 5②).

The algorithms to define an evacuee's neighbors are as follows:

(1) Definition of the neighbors in the view region

As shown in Fig. 5, let the source evacuee be p_i, the location of p_i be L_i, the radius of p_i be r_i, the view field angle be $\theta_i(\theta_i \le 180^\circ)$, the view field radius be d_i, and the velocity vector of p_i be v_i. Let the set of all evacuees in the scene at moment t be S_t, p_j be any other evacuee in S_t, the radius of p_j be r_j, the location of p_j be L_j, the relative velocity vector between p_i and p_j be v_{ij} pointing from p_i to p_j, and the angle between v_{ij} and v_i be θ_{ij}. Set the evacuee set located in θ_i and d_i as S_{t1}, and S_{t1} must then meet the following conditions (Eq. (5)):

$$S_{t1} = \begin{cases} d_{ij} = |L_i, L_j| \le d_i \\ \cos\theta_{ji} = \dfrac{v_i \cdot v_{ij}}{|v_i|\,|v_{ij}|} \ge \cos(\theta_i/2) \end{cases} \quad (i, j \in S_t) \tag{5}$$

where d_{ij} is the distance between p_i and p_j. If $d_{ij} \le d_i$ and $\cos\theta_{ij} \ge \cos(\theta_i/2)$, p_j is in the view region of p_i and can be seen by p_i. The pedestrians in S_{t1} will produce psychological and physical forces on p_i.

(2) Definition of the neighbors out of the view region

In addition to the evacuees who are in the view region, those who are out of the view region but have physical contact will also exert forces on the source evacuee. Let the set of these evacuees be S_{t2}, and then S_{t2} must meet the following conditions (Eq. (6)):

$$S_{t2} = \begin{cases} d_{ij} = |L_i, L_j| \le (r_i + r_j) \\ \cos\theta_{ji} = \dfrac{v_i \cdot v_{ij}}{|v_i|\,|v_{ij}|} < \cos(\theta_i/2) \end{cases} \quad (i, j \in S_t) \tag{6}$$

where $d_{ij} \le (r_i + r_j)$ indicates that p_j has physical contact with p_i. Let the set of all evacuees who produce force on the source evacuee be S; then, S is (Eq. (7)):

$$S = S_{t1} \cup S_{t2}. \tag{7}$$

The pedestrian force on p_i can then be determined by summing the force (f_{ij}) from every evacuee in the set S using Eq. (8).

$$f_i = \sum f_{ij} \quad (j \in S;\ j \ne i). \tag{8}$$

The force (f_{ij}) can be computed using Eq. (2).

2.4. A projection algorithm for the calculation of the evacuee position on stairs

Previous scenarios based on Helbing's social force model occurred on a horizontal surface. However, the transfer activities on stairs involve inclined segments and horizontal aisles rather than a single horizontal plane. Therefore, a projection strategy is adopted to calculate the activities for both inclined and horizontal surfaces simultaneously. According to the

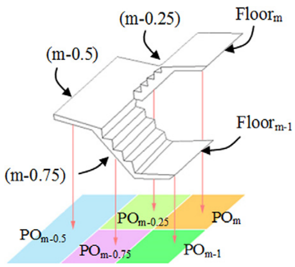


Fig. 6. The projection strategy.

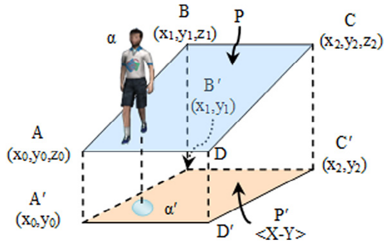


Fig. 7. The retro-projecting strategy.

strategy, all surfaces and transfer activities are projected to a reference horizontal plane, also referred to as the projection field. Accordingly, an evacuee's movement can be calculated using the modified social force model proposed in 2.3. Then, the calculated results, including evacuee velocities and locations, are projected backward from the projection field to the original surfaces of the stair-units. Thus, the activities of all evacuees can be calculated simultaneously. The projecting and retro-projecting algorithms are described below.

(1) Projecting from source surfaces to a reference plane

The ⟨X–Y⟩ plane is chosen as a projection field, onto which the behavior and objects from all surfaces are projected. First, before projecting, all stair-unit planes and floors are assigned with a unique identification (Fig. 6). The floors are identified with integers, for example the first floor is assigned to be 1, and the second floor is assigned to be 2; as for the stair-unit planes, suppose the identification of the upper floor be m, the lower floor be $m-1$, then the identifications of the 3 surfaces of the stair-unit can be assigned as $m-0.25$, $m-0.5$, and $m-0.75$ from top to bottom.

Second, it should be noted that in the projection field, the projected features of the upper floors or upper stair-unit segments will overlap with the projected features of the lower floors or stair-unit segments, so the projection field is assigned a plane-object list (**PL**). Each plane-object (**PO**) in the PL indicates a source floor or a stair-unit plane, and has feature lists such as an evacuee list and an obstacle list. When a feature is projected onto the projection field, it is added to the corresponding feature list of the plane-object to which it belongs. In Fig. 6, for example, the elements on the plane $m-0.75$ will be projected and stored in the evacuee list or the obstacle list of plane-object $PO_{m-0.75}$. Based on this method, all elements used in the social force model including evacuees, walls, boundaries of floors and stair-units, and other obstacles, are projected into the projection field and are further classified by their source floor or stair-unit plane to distinguish the vertical distributions. All forces in P′⟨X–Y⟩ can be calculated using the social force model (Eq. (1)), and the motion features, including the evacuee velocities and locations, can be obtained.

(2) Retro-projecting to source surfaces

As shown in Fig. 7, the source surface is represented by P, and the projection field is P′⟨X–Y⟩. Points A, B, C, and D represent the four corners of P. The corresponding projected points in P′⟨X–Y⟩ are A′, B′, C′, and D′. The edges AB, BC, CD, and DA that form the boundary of P are projected to A′B′, B′C′, C′D′, and D′A′ in P′⟨X–Y⟩. The circle α' is the projected shape of evacuee α.

Let the coordinates of A, B, and C in Fig. 7 be (x_0, y_0, z_0), (x_1, y_1, z_1), and (x_2, y_2, z_2); then, the vectors AB and AC can be given as Eqs. (9) and (10).

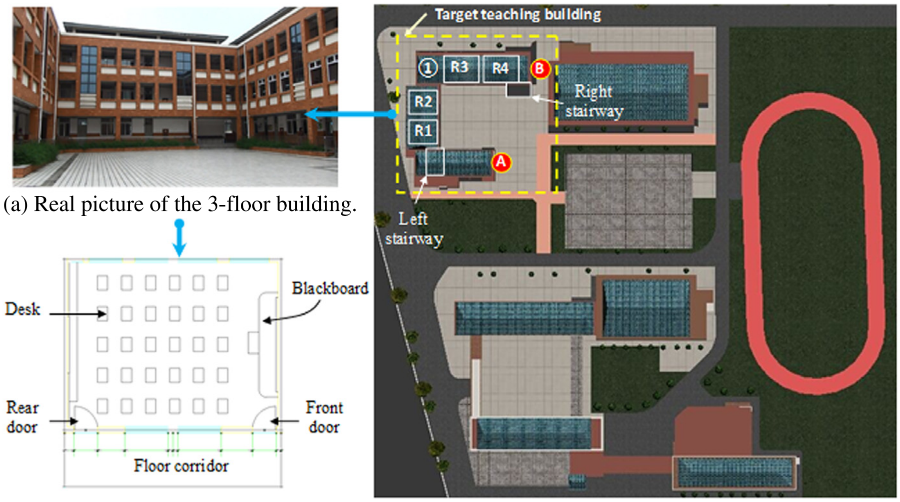
$$\overrightarrow{AB} = [x_1 - x_0, y_1 - y_0, z_1 - z_0] \tag{9}$$

$$\overrightarrow{AC} = [x_2 - x_0, y_2 - y_0, z_2 - z_0]. \tag{10}$$

The normal vector of surface P can be calculated using Eq. (11), and the equation for P can be obtained from Eq. (12).

$$Norm_p = \overrightarrow{AB} \times \overrightarrow{AC} \tag{11}$$

$$\begin{vmatrix} y_1 - y_0 & z_1 - z_0 \\ y_2 - y_0 & z_2 - z_0 \end{vmatrix} \cdot (x - x_0) + \begin{vmatrix} z_1 - z_0 & x_1 - x_0 \\ z_2 - z_0 & x_2 - x_0 \end{vmatrix} \cdot (y - y_0) + \begin{vmatrix} x_1 - x_0 & y_1 - y_0 \\ x_2 - x_0 & y_2 - y_0 \end{vmatrix} \cdot (z - z_0) = 0. \tag{12}$$



(a) Real picture of the 3-floor building.
(b) A plan view of a classroom.
(c) A plan view of the school.

Fig. 8. The layout of the study area.

Suppose that a point $p'(x', y')$ in P′⟨X–Y⟩ is projected from the point $p(x, y, z)$ in P. The coordinate z can be obtained using Eq. (13) by substituting the parameters into Eq. (12).

$$z = f(x', y') = z_0 - \frac{\begin{vmatrix} y_1 - y_0 & z_1 - z_0 \\ y_2 - y_0 & z_2 - z_0 \end{vmatrix} \cdot (x' - x_0) + \begin{vmatrix} z_1 - z_0 & x_1 - x_0 \\ z_2 - z_0 & x_2 - x_0 \end{vmatrix} \cdot (y' - y_0)}{\begin{vmatrix} x_1 - x_0 & y_1 - y_0 \\ x_2 - x_0 & y_2 - y_0. \end{vmatrix}}. \tag{13}$$

Accordingly, the position of any evacuee at any moment on the inclined surfaces and on the horizontal surface of a stair-unit can be calculated.

3. Simulated evacuation on stairs and validations

3.1. Description of the study area and the real drill

(1) The study area

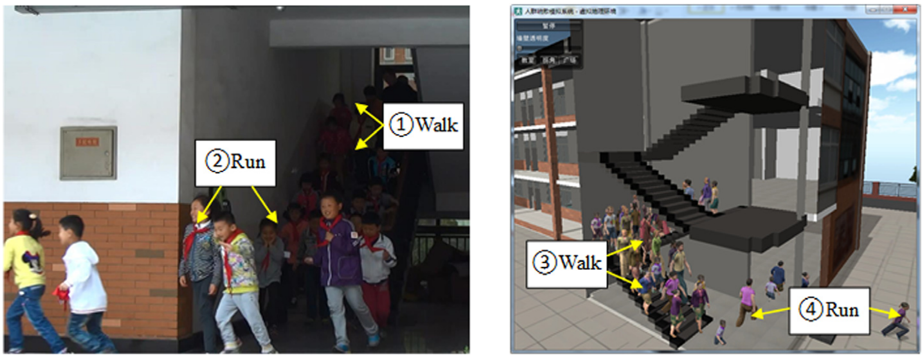
In this paper, a 3-floor classroom building in a primary school in Pinghu City, Zhejiang, China (Fig. 8) was selected. Fig. 8(a) is the layout of the campus of the school. The 3-floor classroom building is on the upper left of the campus, a picture of which is shown in Fig. 8(b). In the classroom building, there are 2 stairways, called the left stairway and the right stairway; there are 4 classrooms on the 2nd floor and the 3rd floor named R1, R2, R3 and R4; on the 1st floor, there are 2 classrooms named R3 and R4. Here, simpler abbreviations were employed; for example, F2_R3 refers to the classroom R3 on the 2nd floor, and F3_R3 refers to the classroom F3 on the 3rd floor and so on. The layout of a classroom (F3_R3) is shown in Fig. 8(c). There are 2 doors including a rear door and a front door by which the classroom connects with the floor corridor. There were 30 second-grade students in each classroom.

(2) The real drill

According to the drill plan, the classes R3 and R4 on every floor evacuate through the right stairwell, and the classes R1 and R2 on every floor evacuate through the left stairwell. At the moment of evacuation, all the students were in class, and the teachers and students ran out of the classrooms from the nearest door, the front door or the rear door into the floor corridor, from which they gained access to the stairways and then evacuated to the ground destinations shown in Fig. 8 A, B. To make the study more concentrated, the 4 classrooms evacuating through the right stairwell, F2_R3, F2_R4, F3_R3 and F3_R4, were selected as the study objects. The classrooms of F1_R3 and F1_R4 on the first floor were excluded because the students in these classrooms did not escape from the right stairwell. The evacuation processes of the 4 classrooms on the floors and in the stairwell were captured by video, based on which motion features such as speed and the evacuee flow were measured and calculated.

(3) Parameter settings for simulation

The modified social force model proposed in Section 2 was employed to simulate the evacuation of the 4 selected classrooms through the right stairwell. The evacuation speed on floors was measured to be 4.0 m/s from the recorded drill video. Therefore, 4.0 m/s was set to be the desired speed of the evacuees; it should be noted that this is a desired speed



(a) Motion changes in the real drill.

(b) Motion changes in the simulated process.

Fig. 9. Contrast of the motion changes in both processes.

that evacuees expect and try to reach; however, in actual simulations, the speed of evacuees is always much lower than the desired speed due to congestion and blocking. The students in front in the stairwell were chosen to measure the evacuation speed in the stairwell because they were not blocked by other students; the result was 0.9 m/s. The physical features of the students were obtained from the statistics data of China in 2010.[1] According to the data, for Chinese children who are 7–9 years old, the average mass is 23.8 kg for boys and 25.5 kg for girls, and the average bust is 59.9 cm. Therefore, 25 kg was assigned as the average weight, and 0.1 m was assigned as the average radius of the simulated pupils. During the simulation, the features of the pupils mentioned above were set randomly within the range of [−35%, 35%] around the average values of the mass and the radius. The other parameters of the social force model were determined as follows: K and κ were 120,000 and 240,000, respectively, as referenced from the values in Helbing [13]; A and B were set to 3.0 and 0.2, respectively; and the maximum desired velocity was 1.3 times the initialized desired velocity, as referenced from the values in Helbing [14]. The width of the stairwell is 1.5 m, and the width of the floor aisles is 2.0 m.

3.2. Qualitative validations of the simulated evacuation with the real drill

In this section, the ***individual*** features of the motion changes of an evacuee in stairs observed in the real drill and the ***group*** features including the congestion phenomena and lane formation, which were typically observed in the real drill and in previous studies [8,12], are selected for qualitative validations.

(1) Motion changes

In the real drill, it was observed that the evacuee's motion was not always running but changed according to location: because the evacuees were primary pupils, they were very careful when they escaped through the inclined stairwells, and they would ***walk*** for a safer evacuation (Fig. 9①); however, when they arrived at floors, stairwell landings and the ground, which are horizontal, the evacuees would ***run*** for a faster evacuation (Fig. 9②). Such features were also reproduced in the simulated evacuation: after evacuees entered a stairwell, they ***walked*** downstairs (Fig. 9③), and when they arrived at the ground, they began to ***run*** (Fig. 9④). Therefore, at the individual level, the simulated evacuation is similar to the real drill.

(2) Congestion at the entrance to a stairwell

In the real drill, because the stairwell (1.5 m) is narrower than the floor aisles (2.0 m), the evacuee flow had to be narrowed when evacuees entered the stairwell; moreover, their speed decreased suddenly due to changing from running to walking, however, the tracing evacuees were still running toward the stairwell. As a result, the tracing evacuees were blocked and the congestion emerged around the entrance of a stair-unit (Fig. 10①). Such a phenomenon was reproduced in the simulated evacuation, and congestion was found at the entrance of each stair-unit (Fig. 10②).

(3) Lane formation

In a stairwell, the evacuees were constrained in a limited narrow space resulting in a crowded flow; evacuees at the rear did not have enough space to overtake those in front but to follow them; at the same time, there was also not enough space for the evacuees to move left or right. Therefore, in crowded stair evacuations, the evacuees tend to move one after another, and a lane phenomenon comes into being. This is a typical feature observed in the real drill (Fig. 11(a)) and in previous stair evacuation studies [8]. Using the schedule-line model and the modified social force model proposed in Section 2, the lane phenomenon was reproduced in the simulated stair evacuation (Fig. 11(b)), which is very similar to the real drill.

Moreover, because the congestion phenomenon and lane formation are key group activities, it can be argued that the proposed models and algorithms can reproduce group features of stair evacuations that are similar to the real drill.

[1] The bulletin of national physique in 2010 (in Chinese). Available from http://www.gov.cn/test/2012-04/19/content_2117320.htm [Accessed 24 May 2016].

(a) Congestion in the real drill. (b) Congestion in the simulated process.

Fig. 10. Contrast of the congestion in both processes.

(a) Lane phenomenon in the real drill. (b) Lane phenomenon in the simulation.

Fig. 11. Lane formation in both processes.

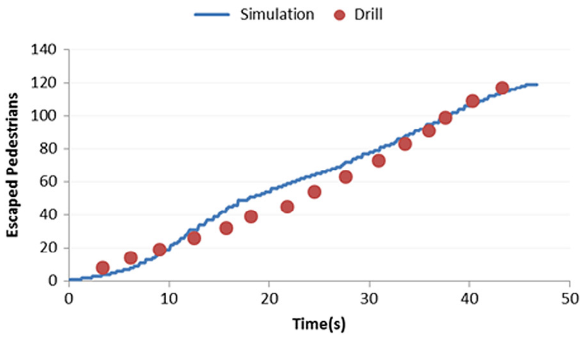


Fig. 12. Contrast of the cumulative escaped evacuees over time in both processes.

3.3. Quantitative validations of the simulated evacuation with the real drill

In this section, 2 common criteria including the cumulative number of escaped evacuees over time [8,11] and the evacuation time [8,11,20] were selected for quantitative validation.

3.3.1. Comparison of the curves of cumulative escaped evacuees

The cumulative number of escaped evacuees over time was chosen as the first quantitative criterion. The criterion refers to the cumulative number of evacuees who have escaped from the stairway to the ground. A curve of the cumulative escaped evacuees is formed as time goes by. The beginning time of the curves of the simulated evacuation and the real drill are calibrated to the moment when the first evacuee has arrived on the ground (Fig. 12). As seen from Fig. 12, both curves almost overlap each other, and the trends over time are indeed similar.

Table 1
Contrast of the sampled escaped evacuees.

Time (s)	Real drill	Simulation	PPCC
3.36	8	4	
6.13	14	8	
9.05	19	16	
12.45	26	31	
15.71	32	44	
18.19	39	51	
21.76	45	59	
24.51	54	64	0.983
27.62	63	72	
30.9	73	79	
33.53	83	87	
35.95	91	95	
37.57	99	99	
40.25	109	107	
43.25	117	114	

Table 2
The TIS of the simulated classes and the real drill.

Item	F2_R3	F2_R4	F3_R3	F3_R4
Average TIS of the class (s)	21.76	17.02	43.91	40.43
Average TIS of this floor in the simulated evacuation (s)	19.40		42.17	
Average TIS of this floor in the real drill (s)	17.11		40.53	

To validate quantitatively, both evacuation curves were sampled at different moments (Table 1). Here, a criterion named the Pearson product-moment correlation coefficient (PPCC) was adopted to calculate the correlation between the sampled data of the real drill and of the simulation. PPCC is a measure of the linear correlation between two variables X and Y (Eq. (14)), giving a value between $+1$ and -1 inclusive, where 1 is total positive correlation, 0 is no correlation, and -1 is total negative correlation.[2] In Eq. (14), X, Y are two sets of variables, N is the variable number in X or Y, and r is the correlation. The escaped evacuees in the real drill at sampled moments (the 2nd column in Table 1) were set as the vector X, and the escaped evacuees in the simulated evacuation at sampled moments (the 3rd column in Table 1) were set as the vector Y; N was the number of sampled moments, i.e. 15; when these parameters were substituted into Eq. (14), the result that was obtained was 0.983. Because the result is close to 1.0, which identifies total positive correlation, it can be argued that the two curves of the real drill and the simulated evacuation are highly similar in time distribution and tendency. The results also indicated that the simulated evacuation is overall and statistically consistent with the real drill.

$$r = \frac{\sum XY - \frac{\sum X \sum Y}{N}}{\sqrt{\left(\sum X^2 - \frac{(\sum X)^2}{N}\right)\left(\sum Y^2 - \frac{(\sum Y)^2}{N}\right)}}. \tag{14}$$

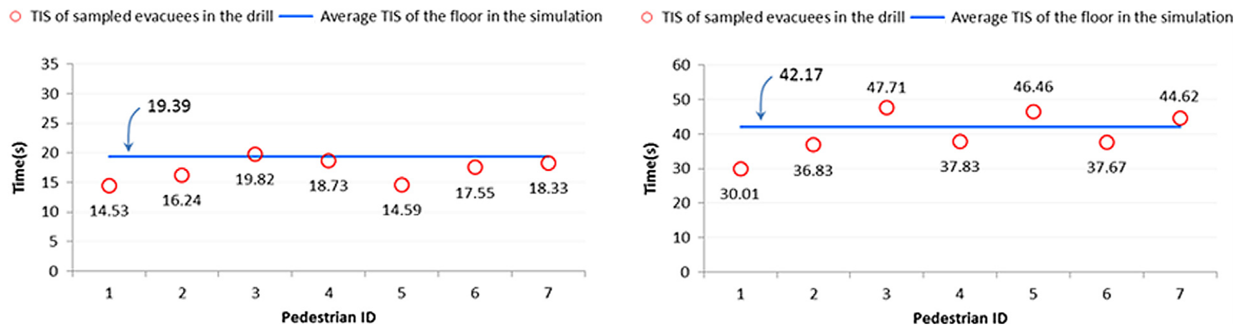
3.3.2. Contrast of evacuation time in the stairway

The evacuation time for an evacuee to escape to the ground that was used in Section 3.3.1 included both the time spent on floors and the time spent in the stairway. To depict the evacuation process in the stairway more accurately, an indicator termed "Time In Stairway (***TIS***)" was proposed and calculated as the moment when an evacuee enters a stairway to the moment when the evacuee escapes out of the stairway to the ground.

Seven students from the 2nd floor and the 3rd floor in the real drill were selected to survey their TIS. The values of the TIS of the sampled evacuees were labeled near the evacuee points as shown in Fig. 13; the average TIS of students from the 2nd floor and from the 3rd floor in the simulated evacuation were also calculated. The results are listed in Table 2.

It can be found that (1) as seen from Fig. 13, the TIS points of the sampled students on both floors in the real drill are distributed around the average TIS line of the corresponding floor in the simulated evacuation, which indicates that the real drill and the simulated evacuation were consistent with each other; (2) when the absolute values were examined (Table 2), as for the evacuees who started the evacuation from the 2nd floor in the simulated evacuation, the average TIS of F2_R3 and F2_R4 were calculated as 21.76 and 17.02 s, resulting in an average TIS of the 2nd floor of 19.40 s, which was close to the average TIS of the 2nd floor in the real drill, 17.11 s. When the average TIS of the 3rd floor were studied, the same result could be found: the average TIS of F3_R3 and F3_R4 were 43.91 s and 40.43 s with an average TIS of 42.17 s which was also

[2] Pearson product-moment correlation coefficient. Available from https://en.wikipedia.org/wiki/Pearson_product-moment_correlation_coefficient [Accessed 24 May 2016].



(a) The 2nd floor. (b) The 3rd floor.

Fig. 13. Contrast of the average TIS of the simulation and the sampled evacuees in the real drill.

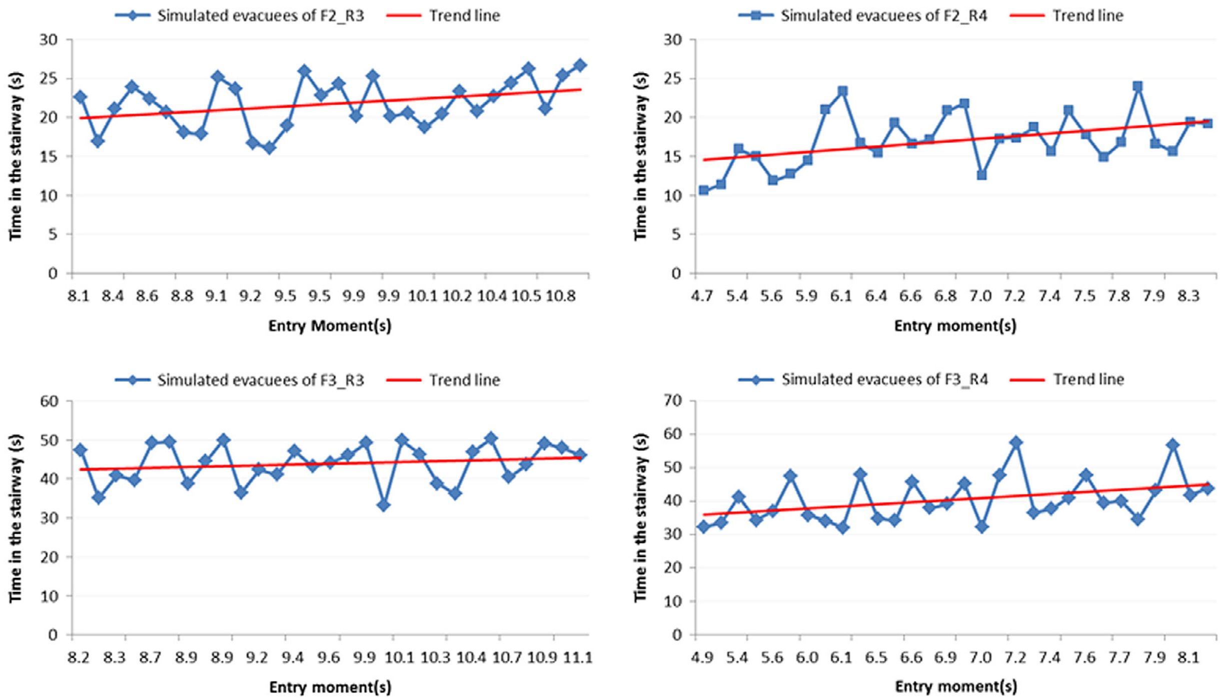


Fig. 14. Relationship between TIS and the moment the stairway is entered for every class.

very close to the TIS of the 3rd floor obtained in the real drill, 40.53 s. Therefore, from the perspective of absolute evacuation time, the simulated evacuation is also consistent with the real drill.

Thus, based on the results obtained in Sections 3.2 and 3.3, it can be concluded that the simulated evacuation process is consistent with the real drill both in the qualitative and quantitative aspects, which proves that the models and the algorithms proposed in Section 2 are correct and credible, and more simulations based on these models can thus be conducted to determine further rules for evacuations on stairs (see Section 4).

4. Results

4.1. Relationship between TIS and the moment the stairway is entered

In the simulated evacuation, when we sort all students' TIS according to the sequential order that they entered the stairway and graph them (Fig. 14), an overall trend is found whereby the later an evacuee enters the stairway, the more TIS the evacuee will spend. Such a trend exists in all classrooms including F2_R3, F2_R4, F3_R3, and F3_R4. The reason can be deduced that in a continuously crowded evacuation, an evacuee who trails behind will closely follow the evacuees in front, and the later an evacuee enters the stairs, the more blocks he/she sustains from the evacuees in front, which results in a longer time spent on stairs.

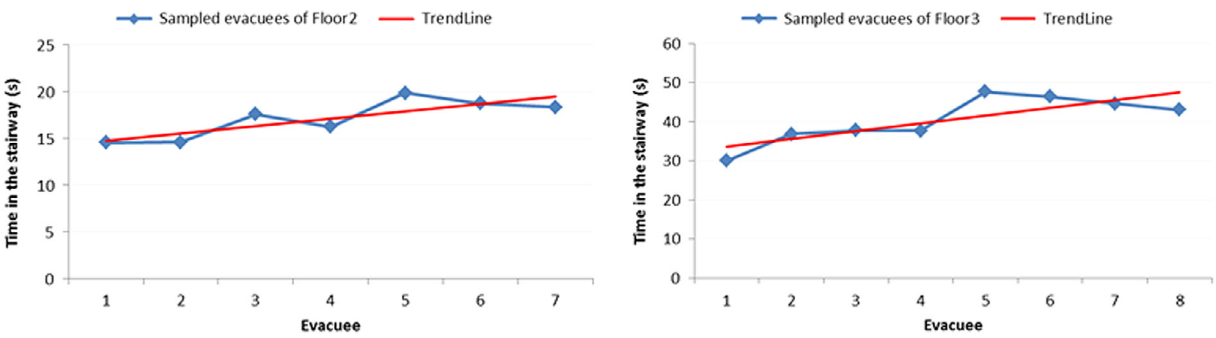


Fig. 15. Relationship between TIS and the moment the stairwell is entered in the real drill.

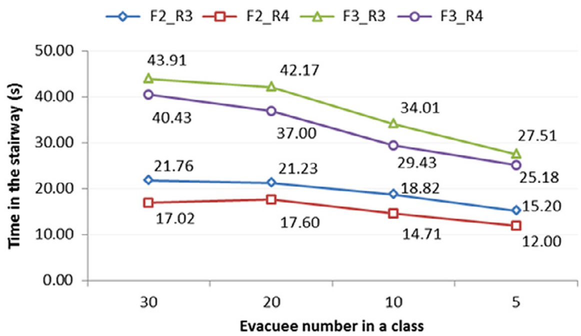


Fig. 16. Relationship between TIS and the number of students in a class.

As for the real drill, when the sampled data used in Fig. 13 were re-sorted according to the moment the stairway is entered, whether the students started the evacuation from the 2nd floor or from the 3rd floor, the same rule applied (Fig. 15): The later a student entered the stairway, the more TIS the student incurred, which is consistent with the rule obtained in the simulation. The result further proves the correctness of the proposed models and algorithms in Section 2.

4.2. Relationship between TIS and the number of students in a class

The impact of the number of students in a class on TIS was studied in this section. Four scenarios were simulated with 30, 20, 10, and 5 students in a class. The *average* TIS of every classroom in every scenario was calculated and graphed as in Fig. 16.

The rules are as follows:

(1) The average TIS of a class decreased with the decrease in the amount of evacuees. In other words, the fewer evacuees there were, the less time was spent in the stairwell. The reason is that with the decrease in the number of evacuees, the probability of congestion and blocking in the stairwell fell, and the impact on the decrease in the evacuees' speed also fell. These factors resulted in a more effective evacuation in the stairway and thus a smaller TIS.

(2) A comparison of the TIS of the 2nd floor and the 3rd floor indicates that the impact of the number of evacuees on the TIS of the 3rd floor was greater than the impact on the TIS of the 2nd floor. This occurred because the evacuees from the 3rd floor were blocked by not only other evacuees from the 3rd floor but also the evacuees from the 2nd floor. As the number of evacuees increased, the evacuees from the 2nd floor were unable to escape out of the stair-unit ***SU***, which links the 2nd floor and the ground, in time; this led to cumulative blocking of the evacuees from the 3rd floor once they arrived at ***SU***; consequently, the TIS of the evacuees from the 3rd floor increased to a greater degree than those from the 2nd floor.

4.3. The impact of the staggered strategy on the total evacuation duration

To reduce the risk of excessive congestion in a stairway, a staggered strategy is sometimes adopted. That is, different classes start the evacuation at different moments. Here, 4 scenarios were used to study the impact of the staggered strategy on the evacuation duration (Table 3). In these scenarios, the classes that were further to the ground on each floor were forced to delay their evacuation for a while to reduce possible congestion. Although the stair evacuation was a critical process in emergency evacuation in the multi-floor classroom building, it was assumed that evacuees were studying in classrooms before evacuations (see Section 3.1(2)) in this paper. In addition to the stair evacuation, a whole evacuation process thus involved the evacuation in classrooms toward floor aisles and the evacuation in the floor aisles toward stairwells. Therefore, to make the evaluation more comprehensive, another criterion named the **T**otal **E**vacuation **D**uration (TED) of an evacuee

Table 3
Different staggered strategy settings.

Scenario	Staggered strategy
S1	No delay for all classes
S2	F2_R3 and F3_R3 were delayed for 2.5 s
S3	F2_R3 and F3_R3 were delayed for 4.9 s
S4	F2_R3 and F3_R3 were delayed for 9.7 s

Table 4
Evacuation time under different staggered strategies (unit: s).

Time	Scenario	F2_R3	F2_R4	F3_R3	F3_R4
TIS	S1	21.58	18.18	44.98	39.01
	S2	21.57	18.38	43.51	40.12
	S3	20.79	18.98	43.31	40.96
	S4	19.81	18.25	41.28	41.50
TED	S1	31.18	24.93	54.98	46.23
	S2	33.41	25.38	55.50	46.87
	S3	34.94	25.91	57.43	47.82
	S4	38.95	25.18	60.29	48.37

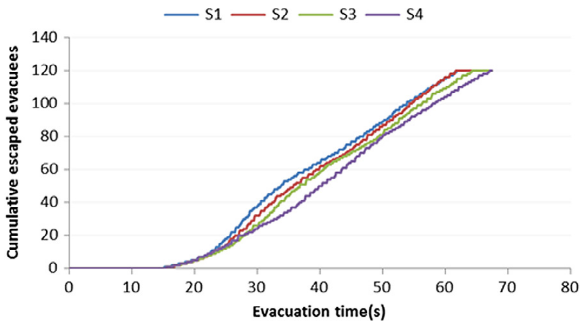


Fig. 17. The curves of cumulative escaped evacuees under different staggered strategies.

was introduced which was calculated as the period from the moment the evacuation started to the moment the evacuee escaped from a stairwell to the ground. The average TIS and the TED of each scenario are listed in Table 4 and graphed in Fig. 17.

It can be seen that with the adoption of the staggered strategy (Table 4), the TIS of the classes, F2_R3 and F3_R3, decreased: When their evacuation moments were delayed for 9.7 s, their TIS decreased by 1.77 s from 21.58 s to 19.81 s and by 3.70 s from 44.98 s to 41.28 s, respectively. Thus, congestion, in particular blocking caused by the classes in front, decreased. However, the TIS of F3_R4, the nearer class on the 3rd floor, experienced an increase in TIS of 2.49 s, from 39.01 s to 41.50 s; that is because the start moment of F2_R3 on the 2nd floor was delayed, more time was necessary for the evacuees from the 2nd floor to pass through the stair-unit that linked the 2nd floor to the ground, and the evacuees from F3_R3 experienced more congestion with the evacuee flow from the 2nd floor, in particular F2_R3, for a longer period of time.

The average TED indicate that except for F2_R4, there is a trend whereby the average TED of each class increased with the increase in the delay duration: When it was delayed by 9.7 s, the average TED of F2_R3 increased by 7.77 s from 31.18 to 38.95 s, while the average TED of F3_R3 increased by 5.31 s from 54.98 to 60.29 s. Therefore, it can be concluded that although the staggered strategy may reduce the TIS of some classes, the decrease in TIS does not match the delayed duration, and the TED of the whole building increases with the increase in the delay duration (Fig. 17). Thus, the staggered strategy is not always the best strategy for the whole building, although the congestion in the stairway may be reduced, and a moderate congestion can improve the efficiency of evacuation.

4.4. The impact of the grade layout on the evacuation time

One of the greatest differences between a classroom building and other multi-floor buildings is that different grades are located within the same building, and these grades may be arranged on different floors, forming a grade layout. Different grade layouts may have a different impact on the evacuation process and evacuation efficiency. Here, two grades, the first grade and the second grade, were selected for comparison, and 4 scenarios with different layouts for the two grades were created (Table 5). Each grade had 2 classes located on the same floor. The running speed of the second grade is 5.0 m/s, and the running speed of the first grade is 4.0 m/s. The curve of the cumulative number of escaped evacuees over time in each scenario is shown in Fig. 18.

Table 5
Grade layout in 4 scenarios.

Scenario	The 2nd floor	The 3rd floor
S1	1st grade	1st grade
S2	2nd grade	2nd grade
S3	1st grade	2nd grade
S4	2nd grade	1st grade

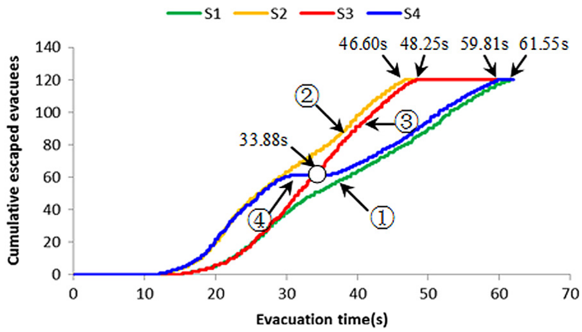


Fig. 18. The curves for cumulative escaped evacuees under different grade layouts.

When the whole building was given the same grades, in S1, the building was given solely first-grade classes (Fig. 18①), and the evacuation duration for the whole building was relatively longer, 61.55 s. In S2, the building was given solely second-grade classes (Fig. 18②), and the evacuation duration of the whole building was relatively shorter, 46.60 s. Therefore, it can be concluded that the evacuation is more efficient when the whole building contains only elder students as opposed to younger students.

When the building was given different grades, the difference between S1 and S4 is the grade on the 2nd floor; in S1, it is the first grade, and in S4, it is the second grade. The evacuation curves of S1 (Fig. 18①) and S4 (Fig. 18②) show that their total evacuation durations were very close, 61.55 s and 59.81 s, respectively. However, the patterns of the two curves are different, indicating different evacuation processes: In the earlier period of the evacuation, the cumulative escaped evacuees in S4 were obviously greater than the escaped evacuees in S1 because the second grades escaped faster; Moreover, in the latter part of the evacuation, the S4 curve is still above the curve of S1, indicating that in this period, the evacuation in S4 was still more efficient than the evacuation in S1. The reason can be deduced that in S4, the first-grade evacuees from the 3rd floor could not catch up with the second-grade evacuees from the 2nd floor, and when the first-grade evacuees arrived at the stairwell that linked the 2nd floor and the ground, there were no more second-grade evacuees and thus the first-grade evacuees experienced no blocking from these evacuees. However, the 2 curves in this period were very close, and the evacuation durations were very similar, implying that in S1 blocking between evacuees from different floors was also minimized as in S4.

A comparison of S3 and S4 (Fig. 18③ and ④) shows that the evacuation patterns were obviously different from each other. In S3 (see curve ③), in which the second grades were deployed on the 3rd floor and the first grades were deployed on the 2nd floor, the number of escaped evacuees increased smoothly and continuously over time, and the total evacuation time was shorter. In S4 (see curve ④), in which the second grades were deployed on the 2nd floor and the first grades were deployed on the 3rd floor, the total evacuation time was obviously longer than that of S2. However, before the point at which 33.88 s is reached – where the two curves intersect – the number of escaped evacuees and the evacuation efficiency of S4 were above those in S3, as the second-grade evacuees from the 2nd floor finished the evacuation in a short time. Therefore, the result provides a reference for how to deploy grades in a classroom building: If the evacuation of the ***whole*** building is critical, the higher grades should be deployed on the upper-level floors, and the lower grades should be deployed on the lower floors; however, if the disaster is serious and the time to evacuate is limited, the higher grades could be deployed on lower floors so that as many people escape as possible within a specific period of time after the disaster.

Moreover, a comparison of the curves of the grade layouts in which the building was given the same grades and the curves of the grade layouts in which the building was given different grades, the S2 and S3 curves as well the S1 and S4 curves, the total evacuations for S2 and S3, as well as those for S1 and S4, were close to each other; however, the S1 and S2 curves increased steadily, indicating that the evacuation process was more stable than in S4 and S3.

Therefore, it can be concluded that (1) the preferred layout for a classroom building is one where all the classrooms are the same grade, so that blocking in the stairways is minimized and a more stable evacuation is achieved; (2) if there are different grades in a classroom building, when the evacuation duration is critical, it is preferable to have the higher grades on the higher floors and the lower-grades on the lower floors; as a consequence, the evacuation has the potential to be more efficient and finish in a relatively short period of time; (3) a layout where higher grades are deployed on the lower floors and the lower grades are deployed on higher floors can result in more escaped evacuees within a specified duration of time.

5. Conclusion and discussion

Previous studies on stair evacuations mainly focused on modeling evacuee behaviors; few focused on modeling the spatial relationship between different parts of a stairwell and the spatial relationship between a stairwell and floors, which determines the boundary of evacuee behaviors and further influences the spatial relationship between evacuee flows on different floors; in addition, few studies focused on the evacuation of a multi-floor classroom building of a primary school, where the evacuee organization and the spatial distribution are different from other multi-floor buildings. In this paper, a stair-unit model was first proposed to describe the spatial topologies of twisting stair-wells and to describe the spatial relationship between stairwells and floors. Based on the model, a schedule-line model was proposed to calculate the path in stair-units and a modified algorithm to determine pedestrian forces was proposed to depict the evacuee activities in stairwells; and a projection algorithm was proposed to calculate 3-dimensional motions in stairwells. The simulated process in a 3-floor classroom building was achieved and compared with a real evacuation drill. The results showed that the simulated evacuation was qualitatively and quantitatively consistent with the real drill which proves that the proposed models are the correct approach.

Further simulations were conducted, and more results were obtained:

(1) Congestion is one of the main reasons for the increase in evacuation time on stairs. The higher the floor is, the greater the congestion is, and the greater the increment of TIS. The impact of congestion is also reflected in evacuation time and the moment of entering the stairs: The later a student enters the stairway, the greater the congestion that is exerted on the student, and the more TIS the student will spend.

(2) The staggered strategy can reduce congestion on stairs and the TIS of some classes. However, for a whole building, the decrease in TIS does not match the delayed duration, and the TED of the whole building increases with the increase in the delay duration. Thus, the staggered strategy is not always preferable, in particular when the total evacuation time of a whole building is considered, which is determined by the evacuation time of the latest class.

(3) The grade layout whereby different grades are located on different floors in a classroom building is one of the most significant differences from other multi-floor buildings. A preferred layout is one where a building has classrooms with the same grade, so that blocking on the stairways is minimized, thus stabilizing the evacuation process. In such layouts, the higher the grades are, the less the total evacuation time is. If there are different grades within the same building, when the evacuation time is critical, it is preferable to deploy higher grades on higher floors and lower grades on lower floors; when higher grades are deployed on lower floors and lower grades on higher floors, more evacuees can escape within a specific duration of time, and such a layout can save more evacuees, in particular when the evacuation time is strictly limited to a very short period.

Finally, as mentioned in Section 1, not only multi-floor classroom buildings are equipped with twisting stairwells but also other buildings such as public commercial buildings and transportation junctions; therefore, the simulation of emergency stair evacuations in such buildings can be achieved and studied using the models and algorithms proposed in this paper.

However, it should be noted that the conclusions obtained in this paper are based on the absence of a fire disaster. When a fire occurs, the evacuation process will be disturbed. For example, if the evacuation routes of some evacuees are blocked by fire, those evacuees would detour to other floors and stairwells, which makes the evacuation process more complex. Therefore, in the future, the impact of fires on the evacuation activities should be modeled, and the spatio-temporal changes in multi-floor classroom buildings as a result of fires should be studied.

Acknowledgments

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References

[1] T.J. Shields, K.E. Boyce, N. McConnell, The behaviour and evacuation experiences of WTC 9/11 evacuees with self-designated mobility impairments, Fire Saf. J. 44 (2009) 881–893.
[2] J. Ma, W.G. Song, W. Tian, S.M. Lo, G.X. Liao, Experimental study on an ultra high-rise building evacuation in China, Saf. Sci. 50 (2012) 1665–1674.
[3] V.A. Oven, N. Cakici, Modelling the evacuation of a high-rise office building in Istanbul, Fire Saf. J. 44 (2009) 1–15.
[4] N.C. McConnell, K.E. Boyce, J. Shields, E.R. Galea, R.C. Day, L.M. Hulse, The UK 9/11 evacuation study: analysis of survivors, Fire Saf. J. 45 (2010) 21–34.
[5] N. Pelechano, A. Malkawi, Evacuation simulation models: challenges in modeling high rise building evacuation with cellular automata approaches, Autom. Constr. 17 (2008) 377–385.
[6] X. Xu, W. Song, Staircase evacuation modeling and its comparison with an egress drill, Build. Environ. 44 (2009) 1039–1046.
[7] L. Yang, P. Rao, K. Zhu, S. Liu, X. Zhan, Observation study of pedestrian flow on staircases with different dimensions under normal and emergency conditions, Saf. Sci. 50 (2012) 1173–1179.
[8] Y. Qu, Z. Gao, Y. Xiao, X. Li, Modeling the pedestrian's movement and simulating evacuation dynamics on stairs, Saf. Sci. 70 (2014) 189–201.
[9] T. Kretz, A. Grünebohm, A. Kessel, H. Klüpfel, T. Meyer-König, M. Schreckenberg, Upstairs walking speed distributions on a long stairway, Saf. Sci. 46 (2008) 72–82.

[10] T. Fujiyama, N. Tyler, Predicting the walking speed of pedestrians on stairs, Transp. Plan. Technol. 33 (2010) 177–202.
[11] W. Lei, A. Li, R. Gao, X. Wang, Influences of exit and stair conditions on human evacuation in a dormitory, Physica A 391 (2012) 6279–6286.
[12] J. Koo, Y.S. Kim, B. Kim, Estimating the impact of residents with disabilities on the evacuation in a high-rise building: A simulation study, Simul. Modell. Pract. Theory 24 (2012) 71–83.
[13] D. Helbing, I. Farkas, T. Vicsek, Simulating dynamical features of escape panic, Nature 407 (2000) 487–490.
[14] D. Helbing, P. Molnár, Social force model for pedestrian dynamics, Phys. Rev. E 51 (1995) 4282–4286.
[15] W. Li, J. Gong, P. Yu, S. Shen, Modeling, simulation and analysis of group trampling risks during escalator transfers, Physica A 444 (2016) 970–984.
[16] W. Li, Y. Li, P. Yu, J. Gong, S. Shen, The Trace model: A model for simulation of the tracing process during evacuations in complex route environments, Simul. Modell. Pract. Theory 60 (2016) 108–121.
[17] W. Li, J. Gong, P. Yu, S. Shen, R. Li, Q. Duan, Simulation and analysis of congestion risk during escalator transfers using a modified social force model, Physica A 420 (2015) 28–40.
[18] W. Li, J. Gong, P. Yu, S. Shen, R. Li, Q. Duan, Simulation and analysis of individual trampling risk during escalator transfers, Physica A 408 (2014) 119–133.
[19] D. Helbing, L. Buzna, A. Johansson, T. Werner, Self-organized pedestrian crowd dynamics: experiments, simulations, and design solutions, Transp. Sci. 39 (2005) 1–24.
[20] Y. Min, Y. Yu, Calculation of mixed evacuation of stair and elevator using EVACNET4, Procedia Eng. 62 (2013) 478–482.