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Experiment, model, and simulation of the pedestrian flow around a training school classroom during the after-class period

Chuan-Zhi Xie[1], Tie-Qiao Tang[1], Bo-Tao Zhang[1] and Heng-Jun Xiang[2]

Abstract
In China, training schools are ubiquitous, where heterogeneous pedestrian flow (which consists of adults and children) widely occurs during the after-class period. In this paper, we develop a fine grid cellular CA model to describe the pedestrian behaviors (e.g., pick-up behavior, searching behavior, matching behavior, waiting behavior, leading behavior, and following behavior) at a training school during the after-class period and explore the effects of the special behaviors on each pedestrian's movement in and around a classroom. To describe the heterogeneous pedestrian flow accurately, (i) some questionnaire surveys are designed to extract some features of adult's and child's movement, and (ii) some video experiments are conducted to estimate/calibrate some parameters of interest in the proposed model. Finally, some strategies are designed to enhance the evacuation efficiency and the operational efficiency of training school. The numerical results indicate that the proposed model can reasonably match with reality, and the proposed strategies can enhance the evacuation efficiency and the operational efficiency of training school. The results can help the administrators to effectively manage the pedestrian evacuation at training school during the after-class period.

Keywords
Training school, fine grid CA model, experiment, pedestrian heterogeneity, evacuation strategy

1. Introduction

In recent years, scholars have conducted extensive and in-depth research on crowd evacuation.[1–5] For example, for the evacuation of dense crowds, Hesham and Wainer[1] presented advanced models based on centroidal particle dynamics (CPD), an agent-based short-range collision-avoidance model for pedestrians in dense crowds. Their models can reproduce visually convincing emergent crowd phenomena. For the evacuation under fire conditions, Xie et al.[2] extended computational fluid dynamics (CFD) model to investigate the fire evacuation in a metro station, and they claimed that their model can contribute to the emergency management; Yuan et al.[3] proposed an extended social force evacuation model considering the effect of emergency signs, and simulation results of their model can help to design the layout of emergency signs. For the evacuation of multistorey buildings, Liu et al.[4] carried out a 3D visual simulation enabling the simulation of building evacuation more realistic; Al-Habashna and Wainer[5] adopted Cellular Discrete EVent System Specification (Cell-DEVS) to simulate multiple-floor buildings' evacuation. Similar to the above research scenarios, China's training schools are also special scenarios with some potential evacuation safety hazards. For example, in March 2013, one safety accident occurred in a training school in Zhejiang, China, where one student died and six students were injured. In May 2016, one safety accident occurred in a training school in Liaoning, China, where three students died. For solving such problems, the relevant government department has required that the pedestrian flow management of training schools should be strengthened. More specifically, not only should each

[1]Beijing Key Laboratory for Cooperative Vehicle Infrastructure Systems and Safety Control, School of Transportation Science and Engineering, Beihang University, Beijing, China
[2]Shenzhen New World Training Co., Ltd, Shenzhen, China

Corresponding author:
Tie-Qiao Tang, Beijing Key Laboratory for Cooperative Vehicle Infrastructure Systems and Safety Control, School of Transportation Science and Engineering, Beihang University, Xueyuan Road 37, Haidian District, Beijing 100191, China.
Email: tieqiaotang@buaa.edu.cn

training school improve the safety of pedestrian evacuation in emergencies, but it also regulates the movement of each pedestrian in nonemergency situations during the after-class period. That is because, for a training school, the effective management of pedestrian flow during the after-class period under non-emergency situations is not only helpful to improve the efficiency of organizing pedestrian evacuation under emergencies but also to improve the operating efficiency of the training school. Hence, it is necessary to regulate the pedestrian flow and explore the corresponding complex phenomena in training schools during the after-class period.

For ordinary schools (e.g., university, middle school, elementary school, and kindergarten), researchers have proposed various models to study the pedestrian flow dynamics and evacuation.[6–13] For the pedestrian flow dynamics under the scenario of university: Liu et al.[6] proposed a video data-driven social force model to simulate the crowd evacuation under the scenario of university and claimed that the proposed model is consistent with real-world situations and can assist in analyzing emergency evacuation scenarios; Delcea et al.[7] chose 18 university students whose ages were between 19 and 21 years old to carry out an experiment under two scenarios (i.e., a classical classroom and a collaborative classroom) and used the experimental results to propose an agent-based model, which can be used to describe the pedestrian flow in the classroom with various configurations. For the pedestrian flow under the scenario of elementary school and middle school: Chen et al.[8] conducted a video observation in a primary school study and proposed an extended cellular automaton (CA) model to depict the movement of children with and without group behavior; Cuesta and Gwynne[9] used semi-announced drill to study the evacuation process at the same school (where the students consist of different age and belong to primary or secondary classes), and used the experimental data to calibrate the average speed of children with different age; considering the school's exposure to natural disasters and the experience of its students, Vásquez et al.[10] studied the perspectives of K-12 students relative to their school's evacuation plan for a major disaster, such as an earthquake and a tsunami; Li et al.[11] studied the evacuation of multifloor classroom buildings in a primary school and proposed a stair-unit model, which can depict the 3D evacuation process in multifloor buildings as well. For the study of pedestrian dynamics under the scenario of pre-school institution (e.g., kindergarten): Najmanová and Ronchi[12] collected data from the two semi-announced evacuation drills conducted in the same pre-school institution in Prague and divided the participants into two groups: junior children and senior children; Kholshchevnikov et al.[13] designed a research in a pre-school educational institution to determine possible values for their pre-movement time and to thoroughly investigate the parameters of their movement along the emergency escape routes.

However, the models[6–13] cannot directly be applied to explore the pedestrian flow at training schools since most training schools have some distinctive features no matter in the non-movement aspects (e.g., more complex pedestrian composition) or in the movement-related aspects (e.g., each child's behavior subjected to the corresponding parent but not the teacher), where the distinct features can be summarized as follows:

(1) Fathers/mothers can stay in the classroom with their children to audit (see Figure 1; https://www.sohu.com/a/234241195_282563).[14] This phenomenon is not seen in the ordinary school frequently. Therefore, the pedestrian composition in the training school is heterogeneous, whereas the counterpart in the ordinary school is homogeneous.[15,16] This heterogeneity shows that the pedestrian behaviors in the training school classroom may be different from those in the ordinary school classroom under emergency and non-emergency situations. Once emergency occurs, each parent will protect his/her child first but not obey the teacher's instructions. Under the non-emergency situation or during the after-class period, each child will be subject to his/her parent but not walk independently. Note: father/mother is called as an adult in this paper.
(2) Except for the obedience of parents to children mentioned in (1), the pedestrians have other unique behaviors[17,18] (e.g., the child's searching behavior, packing behavior, etc.) during the after-class period, which shows that the pedestrian system in the training school is more than one in the ordinary school.
(3) Adults and children have different features (e.g., speed, size, etc.), and the adults (moving to pick up his/her child) and the children (moving to the classroom exit) have different movement destinations.

The above features may be depicted by the previous studies,[19–21] but to better manage the pedestrian flow in the training school classroom, a refined model incorporating the data sources (for calibrating the model), such as pedestrian behavior controlled experiments, and questionnaires in the training school, should be developed, rather than directly applying the previous models. To resolve this problem, we should construct a fine grid CA model to explore the pedestrian flow at training schools. In this paper, we use questionnaire survey to extract some features of the pedestrian flow in the training school classroom, develop a fine grid CA model based on the features, apply video data to estimate/calibrate some parameters of

Figure 1. Two typical scenarios in training school classrooms, where (a) is the one that adults sit together with their children in the classroom, and (b) is the one that adults sit at the back of the classroom.

Table 1. Some variables and the corresponding physical meanings.

Variable	Physical meaning
t_n	The *n*th time step
$N_a^p(t_n)$	The number of adults in the system at t_n
$N_c^p(t_n)$	The number of children in the system at t_n
$P_a^k(k = 1,\ldots,N_a^p)$	The *k*th adult in the system
$P_c^k(k = 1,\ldots,N_c^p)$	The *k*th child in the system
PT_a^k	The pre-motion time of P_a^k
PT_c^k	The pre-motion time of P_c^k
PT_a	The set of PT_a^k
PT_c	The set of PT_c^k
PS_c^k	The pausing time of P_c^k
PS	The set of PS_c^k
i,j	The *i*th row and *i*th column in the system
$C_{i,j}$	Cell (i,j)
$FF_{de}(i,j)$	The floor field that considers the pedestrian density around $C_{i,j}$
$FF_{MD}(i,j)$	The floor field that considers the Manhattan distance between $C_{i,j}$ and the target cell
$FF_{fo}(i,j)$	The floor field considering follow-up behavior
ε_c	Rationality parameter for children
ε_a	Rationality parameter for adults
Θ	Space between seats and desks
$PC_{i,j}$	The pheromone concentration of $C_{i,j}$
$P_w(t_n)$	The number of adults waiting in the corridor at t_n
p_c^{cr}	The proportion of children crossing Θ
p_c^{ac}	The proportion of children accelerating if possible

the proposed model, and finally use the calibrated model to simulate the evacuation process in a training school classroom during the after-class period. This paper is organized as follows: in Section 2, we first extract the movement features of adults and children in training school classroom based on the questionnaire surveys, and then propose an extended fine grid CA model to describe each pedestrian's movement in the classroom during the after-class period; in Section 3, we first use some simulations to validate whether the proposed model can describe some complex phenomena in the given scenario and then propose some strategies to enhance the evacuation efficiency and the operational efficiency of training school; and conclusions are summarized in Section 4.

2. Model

In this section, we first design some questionnaire surveys to extract some basic features of adult's and child's movements at a training school, then propose a fine grid CA model to depict each pedestrian's movement in and around a classroom during the after-class period, and finally design video experiments to estimate/calibrate some parameters. Some variables and notations are defined in Table 1.

2.1 Scenario

Discrete and continuous models are widely used to study pedestrian flow or traffic flow.[22–25] However, considering

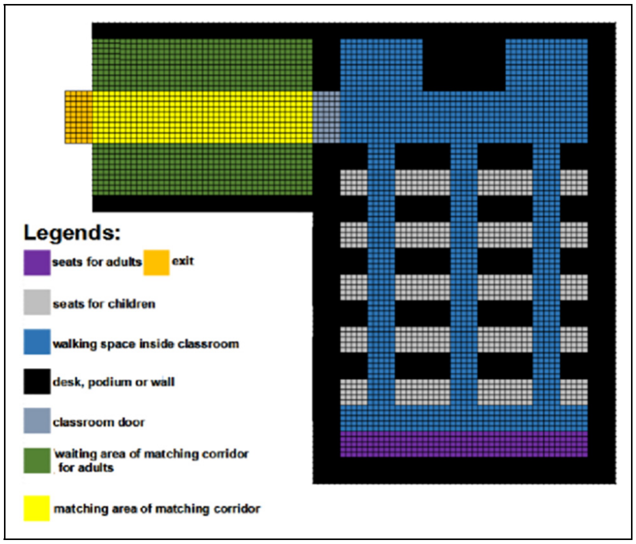

Figure 2. The scenario at a training school during the after-class period.

the real scenarios and research objectives, the CA model is used in this paper. For the CA model, the space needs to be discretized. Thus, in this paper, the research scenario is defined as follows:

(1) The pedestrian movement space includes a classroom, a corridor, a door, an exit and some obstacles that consist of chairs, desks, a podium, and walls (see Figure 2).
(2) The pedestrians consist of adults and children, which show that each pedestrian's size is different. Generally, the sizes of adults are larger than those of children.[26] The study focuses on a classroom of a training school, in which children's age and adults' age are similar. This paper mainly considers the behavior heterogeneity between children and adults and the influence of adults' existence on children. Thus, we choose to ignore the heterogeneity among children or adults. For simplicity, we assume that the body sizes of each adult and child are 0.5 m × 0.5 m and 0.4 m × 0.4 m, respectively.[26]

The CA model is widely used to explore the evacuation from various scenarios, but the traditional CA models assume that each pedestrian occupies only one cell whose size is 0.4 m × 0.4 m.[27] Therefore, the traditional CA models cannot directly be used to study the heterogeneous pedestrian flow in training schools, and we should refine the cell size and propose an extended CA model to study the evacuation process in the tested scenario during the after-class period. Actually, proper discretization can enhance the reliability of simulation results,[28,29] and the discretization schemes in Li and Han[28] and Fu et al.[29] can satisfy the requirements of the adults' and children's body sizes as the criterion for the spatial refinement in the training school classroom. Based on the above discussions, we here define the cell size as 0.1 m × 0.1 m. This shows that each adult occupies 5 × 5 cells, and each child occupies 3 × 3 cells. In addition, we should give the following assumptions and notes:

(1) Each cell is empty or occupied by an obstacle or a pedestrian.
(2) There are two kinds of chairs in the classroom, where the seat for child is matched with a desk, and the one for adult is independently placed at the classroom back. Based on the Chinese National Standard, the chair length and width in the primary school classroom is 0.55 m-0.6 m, and the total length of a desk–chair pair is approximately 1 m. However, due to the space constraint, the desks and chairs in the training school classroom are smaller than the ones in the ordinary school classroom. Thus, the sizes of desks and chairs are set as 0.5 m × 0.5 m (i.e., 5 × 5 cells). Likely, due to the space constraint, only some adults can enter the class in most training schools. Here, we define the number of children chairs as 30 and the proportion of adults (who stay in the classroom) as 0.3, where the 30 children randomly sit on their chairs, whereas nine adults randomly sit on their chairs in reality.
(3) The podium is located in front of the classroom, where the podium size is 1 m × 1.5 m (i.e., the podium occupies 10 × 15 cells); all teaching tools are placed on the podium; the exit size is 1 m × 0.5 m (i.e., the exit occupies 10 × 5 cells).
(4) The door is located on the upper left side of the classroom, which connects the classroom and the corridor. The Chinese standards show that the width of the primary school classroom door cannot be less than 0.9 m (http://www.soujianzhu.cn/Norm/JzzyXq.aspx?id=215). Similarly, the training school classroom door should ensure that two pedestrians can pass simultaneously and also some adults can enter the classroom, so we assumed that the width of training school classroom door could be 1 m.
(5) The adults who do not enter the class are randomly distributed in the two waiting areas (that are located on the upper and lower sides of the corridor, where each waiting area size is 1 m × 3.5 m) during the after-class period; the adults and their children are matched in the matching area; all adults and children walk toward the exit from the matching region.
(6) Each adult only leads his/her child.

In this paper, we selected a single classroom and a corridor (connecting this classroom with the training school exit) as the research scenario, but did not choose the whole training school as the tested scenario, where the reasons are as follows:

(1) It is necessary to explore the pedestrian flow at the whole training school, but few researchers cared the features of pedestrian movement in the tested scenario at the current stage.
(2) Each pedestrian's running time in the tested scenario is relatively short during the after-class period, but if we deeply explore the pedestrian flow system in this area, the simulation results can lay a solid foundation for enhancing the overall evacuation efficiency of the training school with more complex configuration.

2.2 Questionnaire survey

To more accurately depict the pedestrian dynamics in training school, some questionnaire surveys are designed to extract some features of pedestrian flow in the Shenzhen New World Training School. The pedestrian flow in training school consists of adults and children, and the behaviors of adults and children may have differences. Thus, questionnaire surveys for adults and children are designed respectively. The detailed questionnaire surveys will be listed in Appendix I.

2.3 Pedestrian movement model

Based on the pedestrian flow features (extracted based on questionnaire surveys) at training school, we develop a fine grid CA model to depict the pedestrian flow in a training school classroom and a corridor connecting the training school exit and the classroom during the after-class period. To better introduce the model, we divide the pedestrian behaviors during the after-class period into the movement behavior and the matching behavior. The matching behavior in the classroom can be sorted into two parts, that is,

(1) Each adult walks toward his/her child.
(2) This child waits at his/her seat until his/her adult reaches his/her seat.

Likely, the matching behavior in the corridor can be sorted into two parts, that is,

(1) Each child searches his/her adult at the classroom door and walks toward his/her adult.
(2) The corresponding adult waits until his/her child reaches his/her position.

In this paper, we apply the proposed extended fine grid CA model to describe each pedestrian's movement in the classroom and in the corridor during the after-class period. In this CA model, the factors that determine each pedestrian's movement behavior can be formulated as follows:

(1) The spatial distance between his/her current location and expected destination
(2) The attraction between him/her and his/her adjacent pedestrians
(3) The impacts of other pedestrians and obstacles
(4) The attraction caused by the corresponding adult–child pair

The above factors and their impacts on each pedestrian's movement behavior have dynamic features, so each pedestrian's movement behavior has dynamic features. This shows that the proposed model can reproduce each pedestrian's movement behavior during the after-class period.

The results of questionnaire surveys show all adults in the classroom walk to their children's position and walk together, so the children should pack their belongings and wait for their adults. As for other children, they should pack their belongings, leave the classroom, match with their adults in the corridor, and leave the exit together. After matching, all adults lead their children and leave the exit together. The above discussions indicate that we should respectively propose two pedestrian flow models to depict the adult's and the child's movements. Before developing the two models, we should give the following assumptions and notes:

(1) Each pedestrian's movement is discretized in space and time, and the spatial dispersion is determined by the step-lengths of space and time. For individual, the child's normal walk speed (i.e., walking pace as 0.4 m at each time step) and the adult's normal walk speed (i.e., walking pace as 0.5 m at each time step) are respectively set as 1 m/s and 1.25 m/s; when walking alone, the child's walk speed is 1.25 m/s if accelerating; for adult–child pair, the walk speed is set as 1 m/s since adults should adjust their speed to synchronize with their children. In addition, the time-step length is set as 0.4 s. Based on the questionnaire surveys, we can define the lengths of child's and adult's walk paces as 0.2 m–0.5 m (i.e., the walk speed is within 0.5 m/s–1.25 m/s, where the minimum graduation is 0.25 m/s) and 0.3 m–0.5 m (i.e., the walk speed is within 0.75 m/s–1.25 m/s, where the minimum graduation is 0.25 m/s), respectively.
(2) Children and adults will first pack their belongings after class, so we should respectively define the pre-motion time for children and adults (i.e., PT_c, PT_a). Generally speaking, PT_c is larger than PT_a since children naturally have more belongings need packing than adults when having class.

If the numbers of children and adults are enough, the two parameters are likely to fit the normal distribution. In Section 2.4, we introduce the estimation of the two parameters (by using the data of video experiments). Note: all the children participating in the video experiment also participated in the questionnaire survey. Due to the limitation of the sample size and the similarity of the children's behavior under the same scenario, the values of PT_c and PT_a extracted from the video data do obey uniform distribution, where some quantitative features are studied in Section 2.4. In addition, the proposed model in this paper is based on the features of each pedestrian's movement, so we can ignore the randomness of the two parameters and assume that the two parameters follow uniform distribution.

(3) As for the children whose adults are outside the classroom, they first evacuate from the classroom and enter the corridor, then match with their adults and walk to the exit with their adults. As for the children, their movement can be sorted into three steps, where the first step is finished in the classroom, and the second and third steps are finished in the corridor before and after pick-up, respectively. The children whose adults are in the classroom always walk with their adults during the pickup process.

(4) Based on the above pedestrian movement features (especially the last result) extracted from the questionnaire surveys, the selection priority of walk position can be ranked as follows: the priority of each individual child is larger than that of each adult–child pair.

(5) When a pedestrian arrives at the training school exit at t_n, he/she will be removed from the system at t_{n+1}.

First, we should explore the movements of the adults in and outside the classroom, respectively. As for the adults in the classroom, we can sort their behaviors into two parts, that is, packing their belongings at their chairs and walking to their children's position. In addition, the adults' movements can be sorted into three parts, that is, walk in the classroom before and after the pick-up process, and walk in the corridor. To better depict the adults' behavior, we should define PT_a for the adults. For simplicity, we assume that PT_a obeys a uniform distribution within a range. As for the kth adult in the classroom before the pick-up process, his/her transition probability at $C_{i,j}$ (which is in the neighborhood of $C_{x,y}$), $p_a^k(i,j)$, can be defined as follows:

$$w_a^k(i,j) = a_{i,j}^k \cdot f_{i,j}^k \cdot s_{i,j}^k \cdot e^{-\varepsilon_a \cdot \left(\alpha_a \cdot FF_{MD}^c(i,j) + \beta_a \cdot FF_{de}(i,j)\right)}, \quad (1)$$

$$N = \sum_{i=x-5}^{i=x-3} w_a^k(i,y) + \sum_{i=x+3}^{i=x+5} w_a^k(i,y) + \sum_{j=y-5}^{j=y-3} w_a^k(x,j) + \sum_{j=y+3}^{j=y+5} w_a^k(x,j), \quad (2)$$

$$p_a^k(i,j) = w_a^k(i,j)/N, \quad (3)$$

where $a_{i,j}^k, f_{i,j}^k, s_{i,j}^k$ are three binary variables; $FF_{MD}^c(i,j)$ is the floor field that considers the Manhattan distance between $C_{i,j}$ and the position of the kth child; α_a, β_a are two parameters, which are related to $FF_{MD}^c(i,j), FF_{de}(i,j)$, respectively. Note: the values of α_a and β_a can determine whether the destination and the surrounding pedestrians have the quantitative impacts on the pedestrian's choice of moving position when making a movement decision. Here, $a_{i,j}^k, f_{i,j}^k, s_{i,j}^k$ satisfy the following conditions:

$$a_{i,j}^k = \begin{cases} 1, & \text{if } C_{i,j} \text{ emtpy} \\ 0, & \text{otherwise} \end{cases}, \quad (4a)$$

$$f_{i,j}^k = \begin{cases} 0, & \text{if } FF_{MD}^c(i,j) > FF_{MD}^c(x,y) \\ 1, & \text{otherwise} \end{cases}, \quad (4b)$$

$$s_{i,j}^k = \begin{cases} 0, & \text{if } C_{i,j} \in \Theta \\ 1, & \text{otherwise} \end{cases}, \quad (4c)$$

From Equations (1)–(3), we can obtain the following notes:

(1) For each adult in $C_{x,y}$, his/her extended V–N neighborhoods have 12 cells, that is, $j = y \pm 3, y \pm 4, y \pm 5$ if $i = x$, and $i = x \pm 3, x \pm 4, x \pm 5$ if $j = y$.
(2) $w_a^k(i,j)$ and N are two process variables to calculate $p_a^k(i,j)$.

When the adults in the classroom leave their chairs, there may exist bidirectional pedestrian flow at the last row of classroom if two or more adults move in the opposite direction. Thus, it is difficult to depict the bidirectional pedestrian flow by using Equations (1)–(4). Therefore, we should simplify this behavior by applying the following rule: if two adults are about to switch positions, their speed will halve.[30]

After the kth adult in the classroom arrives at his/her child's position and matches with his/her child, we can use Equation (3) to calculate $p_a^k(i,j)$ as long as we rewrite Equations (1) and (2) as follows:

$$w_a^k(i,j) = a_{i,j}^k \cdot f_{i,j}^k \cdot s_{i,j}^k \cdot e^{-\varepsilon_a \cdot \left(\alpha_a \cdot FF_{MD}^{do}(i,j) + \beta_a \cdot FF_{de}(i,j)\right)}, \quad (5)$$

$$N = w_a^k(i-4,y) + w_a^k(i+4,y) + w_a^k(x,j-4) + w_a^k(x,j+4), \quad (6)$$

where $FF^{do}_{MD}(i,j)$ is the floor field that considers the Manhattan distance between $C_{i,j}$ and the classroom door. Here, we consider the following notes:

(1) For each adult in $C_{x,y}$, his/her extended V–N neighborhoods have four cells, that is, $j = y \pm 4$ if $i = x$ and $i = x \pm 4$ if $j = y$.
(2) The reason why redefining the extended V–N neighborhoods is to describe the phenomenon that the adults adjust their pace to walk together with their children.
(3) Overall, the adult's movement model does ensure that the adults in the classroom first move toward their children's position, and then pick their children up. Note: this behavioral feature can be extracted from the questionnaire survey. It is undeniable that if more adults and children are surveyed, some adults in the classroom may pick up their children in the corridor (i.e., the adults directly move toward the classroom door and the adult–child pair is formed in the corridor). However, the proposed model is based on the features of each pedestrian's movement, so other types of adult–child matching patterns are not considered but are indeed worthy of being studied in the future.

Similarly, we can use Equations (3) and (6) to obtain the transition probability of the *k*th adult in the corridor as long as we rewrite Equation (5) as follows:

$$w^k_a(i,j) = a^k_{i,j} \cdot f^k_{i,j} \cdot c^k_{i,j} \cdot e^{-\varepsilon_a\left(\alpha_a \cdot FF^{ex}_{MD}(i,j) + \beta_a \cdot FF_{de}(i,j)\right)}, \quad (7)$$

where $FF^{ex}_{MD}(i,j)$ is the floor field that considers the Manhattan distance between $C_{i,j}$ and the exit; $c^k_{i,j}$ is a binary variable that can be set as follows:

$$c^k_{i,j} = \begin{cases} 1, & \text{if } C_{i,j} \text{ lies in the center of corridor or classroom door} \\ 0, & \text{otherwise} \end{cases}. \quad (8)$$

Next, we explore the child movement, which can be sorted into two cases, that is, the individual movement and the adult–child pair's movement. In addition, each child needs to pack his/her belongings before he/she moves, so we should define PT_c for children. Here, we assume that PT_c obeys one uniform distribution within one range and is larger than that of adults. For this parameter value, refer Section 2.4.

Similar to the adults in the classroom, the transition probability of the *k*th child who walks alone in the classroom can be defined as follows:

$$w^k_c(i,j) = a^k_{i,j} \cdot f^k_{i,j} \cdot s^k_{i,j} \cdot e^{-\varepsilon_c\left(\alpha_c \cdot FF^{do}_{MD}(i,j) + \beta_c \cdot FF_{de}(i,j)\right)}, \quad (9)$$

$$N = \sum_{i=x-4}^{i=x-2} w^k_c(i,y) + \sum_{i=x+2}^{i=x+4} w^k_c(i,y) + \sum_{j=y-4}^{j=y-2} w^k_c(x,j) + \sum_{j=y+2}^{j=y+4} w^k_c(x,j), \quad (10)$$

$$p^k_c(i,j) = w^k_c(i,j)/N, \quad (11)$$

where $p^k_c(i,j)$ is the *k*th child's transition probability at $C_{i,j}$ which is in the neighborhood of P^k_c; α_c and β_c are two parameters that are related to $FF^{do}_{MD}(i,j)$ and $FF_{de}(i,j)$, respectively, and their meanings are the same as those of α_a and β_a. Here, we should give the following notes:

(1) If the *k*th child lies in $C_{x,y}$, his/her extended V–N neighborhoods include 12 cells, that is, $j = y\pm2, y\pm3, y\pm4$ if $i = x$ and $i = x\pm2, x\pm3, x\pm4$ if $j = y$.
(2) $w^k_c(i,j)$ and N are two process variables to calculate $p^k_c(i,j)$.
(3) Some children may cross Θ and some children may accelerate if possible. For convenience, here we list the children crossing Θ in the set Λ, and the children accelerating in the set Ω. Thus, we can calculate $s^k_{i,j}$ based on the following rules:
    (i) As for the *k*th child who does not belong to Λ: if $C_{i,j} \in \Theta$, $s^k_{i,j} = 0$, otherwise $s^k_{i,j} = 1$.
    (ii) As for the *k*th child who belongs to Λ: if $C_{i,j} \in \Theta$, $s^k_{i,j}$ is set as 1 at this cell, otherwise $s^k_{i,j} = 0$; if $\forall C_{i,j} \notin \Theta$, $s^k_{i,j} = 1$.
(4) If a child belongs to Ω, he/she may accelerate (i.e., his/her walk pace may be equal to five cells).

As for the children who walk alone in the matching corridor, we can use Equations (10) and (11) to calculate his/her transition probability as long as we rewrite Equation (8) as follows:

$$w^k_c(i,j) = a^k_{i,j} \cdot f^k_{i,j} \cdot c^k_{i,j} \cdot e^{-\varepsilon_c\left(\alpha_c \cdot FF^{a}_{MD}(i,j) + \beta_c \cdot FF_{de}(i,j)\right)}, \quad (12)$$

where $FF^a_{MD}(i,j)$ is the floor field that considers the Manhattan distance between $C_{i,j}$ and the *k*th adult's position. Note: the children belonging to Ω will also accelerate in the matching corridor if possible.

After the *k*th child matches with his/her adult, Equation (11) can be used to calculate his/her transition probability if Equations (9) and (10) are rewritten as follows:

$$w^k_c(i,j) = a^k_{i,j} \cdot f^k_{i,j} \cdot c^k_{i,j} \cdot e^{\varepsilon_c \cdot \gamma_c \cdot FF_{fo}(i,j)}, \quad (13)$$

Figure 3. Schematic diagram of video experiment, where red circles denote the volunteers (i.e., adults) and the blue ones denote the children.

$$N = w_c^k(i-4,y) + w_c^k(i+4,y) + w_c^k(x,j-4) + w_c^k(x,j+4). \quad (14)$$

where γ_c is a parameter related to $FF_{fo}(i,j)$.

In addition, the children whose adults are outside the classroom will stop at the classroom door to search their adults and leave the door only after they confirm their adults' positions, which indicates that the children have the pausing time at the door. Tang et al.[18] mentioned the pausing time but did not calibrate it. Here, we conducted some video experiments in Shenzhen New World Training School to estimate/calibrate the pausing time (see Figure 3). Using the video experiment that contains 16 adult–child pairs (due to lack of adult participants, we choose 16 volunteers to replace the 16 adults; in this video experiment, each volunteer holding up a plate with a number is staying at the waiting area of corridor, where the number is defined as this volunteer's No., and each child has his/her No. (that corresponds to that of a volunteer) and should remember his/her volunteer's No.; when each child reaches the classroom door, he/she will first search the volunteer's No., then confirm his/her volunteer, and finally match with this volunteer and walk toward the exit together), we can conclude the following quantitative relationships:

$$PS \sim \begin{cases} U(3,4) & 9 < P_w(t_n) \leqslant 16 \\ U(2,2.5) & 5 < P_w(t_n) \leqslant 9 \\ U(1.5,2) & 2 < P_w(t_n) \leqslant 5 \\ U(0.4,0.5) & P_w(t_n) \leqslant 2 \end{cases} . \quad (15)$$

Equation (15) shows that each child's pausing time is positively correlated with the number of pedestrians within his/her sight. (Due to the limited conditions, many children in the training school are chosen to participate in the experiment as possible as we can. We tried to use an alternative method for experiments, but it is undeniable that the sample size is still small, and the impacts of the alternative approach may be insufficient. Large-scale experiments, which involve children and their adults, are indeed needed to calibrate PS, but the proposed model is based on the research object of designed experiments, and the value of PS has relatively little influence on the result qualitatively.) Moreover, Xiao et al.[31] found that most pedestrians prefer large space (i.e., low local density) under nonemergency evacuation. The video data show that the classroom door and corridor can accommodate two pedestrians to walk on shoulder, but most pedestrians walk in the corridor center since the local density is relatively low (see the third feature of the questionnaire surveys).

Finally, we explore how to calculate FF_{MD}, FF_{de}, and FF_{fo}. Here, we use FF_{MD}^{do} as one example to introduce how to calculate the above floor field values, where the detailed algorithms are shown in Table 2.

When we calculate FF_{de}, the pedestrian occupancy and the obstacle occupancy should be considered. For the child who walk alone, if he/she is in $C_{x,y}$, the $FF_{de}(i,j)$ of the empty $C_{i,j}$ (i.e., $j = y\pm2, y\pm3, y\pm4$ when $i = x$; $i = x\pm2, x\pm3, x\pm4$ when $j = y$) can be defined as follows:

$$FF_{de}(i,j) = \frac{N_{oc}^{pe}(i,j)}{1 + N_{nm}(i.j)}, \quad (16)$$

where $N_{nm}(i,j)$ denotes the total number of cells belonging to the Moore neighborhoods of $C_{i,j}$ (here, $N_{nm}(i,j)$ is set as 8); $N_{oc}^{pe}(i,j)$ denotes the total number of cells that belong to the Moore neighborhoods of $C_{i,j}$ and is occupied by other pedestrians.

As for FF_{fo}, researchers used the ant colony pheromone to study the group behavior between pedestrians.[20,32] This pheromone is spatially contagious, that is, with the increase of the distance between the position and the information source, the pheromone centration drops but the dropping rate drops.[33] This property is consistent with the classic pheromone, so for simplicity we can define the following equation:

$$PC_{i,j}^{t+\Delta t} = PC_{x,y}^{t} \cdot \chi\left((x-i)^2, (y-j)^2\right), \quad (17)$$

where $PC_{x,y}^{t}$ denotes the pheromone concentration at cell $C_{x,y}$ at time t; $\chi(i,j)$ is the pheromone diffusion function in the two-dimensional (2D) space and satisfies $\frac{\partial(\chi(i,j))}{\partial i} \leqslant 0$, $\frac{\partial^2(\chi(i,j))}{\partial i^2} < 0$, $\frac{\partial(\chi(i,j))}{\partial j} \leqslant 0$, and $\frac{\partial^2(\chi(i,j))}{\partial j^2} < 0$.

To depict the adult–child pairing behavior, which is not only compact but also with a certain degree of freedom (i.e., adult–child cannot be considered as a single rigid body), we can apply Equation (17) to construct the following two equations:

$$FF_{fo}{}^{t+\Delta t}(i,j) = A \cdot FF_{fo}{}^{t}(x,y) \cdot \chi\left((x-i)^2, (y-j)^2\right), \quad (18)$$

Table 2. The calculation of FF_{MD}^{do}.

Step 1: Set $m = 0$; FF_{MD}^{do} of obstacles (e.g., wall, chair, and desk) are set as 2000; FF_{MD}^{do} of cells occupied by the classroom door are set as 0, and FF_{MD}^{do} of other empty cells are set as 1000.
Step 2: Search the FF_{MD}^{do} values of the four cells belonging to the V–N neighborhoods of the current cell. For these cells, if the FF_s^d value is equal to 1000, set the FF_{MD}^{do} value as $m + 1$.
Step 3: Repeat Step 2 until the FF_{MD}^{do} values of all empty cells are less than 1000.

$$FF_{\mathrm{fo}}{}^{t}(x,y) = \begin{cases} 1, & \text{if } P_a^k \text{isat} C_{x,y} \\ 0, & \text{otherwise} \end{cases}, \tag{19}$$

$$A = \begin{cases} 1, \text{if} i = x \text{ and } j = y \\ 0, \text{otherwise} \end{cases}. \tag{20}$$

Based on the above discussions, we can apply Equations (18)–(20) and the proposed children's motion model (i.e., Equations (13) and (14)) to depict the children's movement after the adult–child pair is formed. Overall, this study is different from Tang et al.[17,18] where the differences are as follows:

(1) The proposed model considers the body size and the walk speeds of adults and children.
(2) Based on a variety of experimental methods, the proposed model considers a more realistic adult–child pairing and matching behavior, but the models in Tang et al.[17,18] simplified the paring and matching behavior as a rigid effect.
(3) The proposed model simultaneously considers the classroom and the corridor outside as the tested scenario, but the classroom and the corridor are set two separate tested scenarios, respectively, in Tang et al.[17,18]

2.4 Estimation/calibration of some parameters

In this subsection, we apply the questionnaire surveys and video data to estimate/calibrate some parameters of the proposed model. (The parameters' estimation is a direct reflection of the results of questionnaire surveys and video data. In this paper, questionnaire surveys, video experiments, and simulations study used precisely for the same pedestrian group. Therefore, the parameters estimated in this paper should be considered as definite simulation premises. When applying this CA model to other pedestrian movements in different scenarios or different pedestrian composition conditions, it is necessary to extract the exact pedestrians' behavior characteristic data and modify the simulation premise parameters.) As for some quantitative results of questionnaire surveys, we list them in Appendix II.

The results of questionnaire surveys indicate that some children may accelerate or cross Θ if possible, so we need to estimate/calibrate p_c^{ac}, p_c^{cr}. Using the data provided by the questionnaire surveys, we can define the estimated values of p_c^{ac}, p_c^{cr}, respectively, as follows:

$$\hat{p}_c^{ac} = \frac{NQ_c^{10}}{NQ_c}, \tag{21}$$

$$\hat{p}_c^{cr} = \frac{NQ_c^{13,a} + NQ_c^{13,b} + NQ_c^{13,c} + NQ_c^{13,e} + NQ_c^{13,f} + NQ_c^{13,g}}{6 \times NQ_c}, \tag{22}$$

where $\hat{p}_c^{ac}, \hat{p}_c^{cr}$ are respectively the estimated values of $p_c^{ac}, \hat{p}_c^{cr}$; NQ_c^{10} is the number of questionnaires where each respondent accelerates based on Q10; NQ_c is the valid number of children's questionnaires; $NQ_c^{13,i}$ is the number of questionnaires that the respondent crosses Θ based on Q13(i) (here, $i = a, b, c, e, f, g$). Using the data provided by the questionnaires, we can respectively calibrate p_c^{ac}, p_c^{cr} as follows:

$$p_c^{ac} = 0.32, p_c^{cr} = 0.34. \tag{23}$$

The sample estimation of children's behavior parameters (i.e., p_c^{ac}, p_c^{cr}) involved in this study is used as unbiased estimation of all children's (i.e., population) behavior parameters under the same environment, where the detailed proof is listed in Appendix III.

Next, we estimate/calibrate PT_a, PT_c. Here, we use some video experiments conducted in Shenzhen New World Training School to estimate/calibrate PT_c, where two screenshots of field video experiments are shown in Figure 4. Using the video data, we can calibrate PT_c, PT_a (here, the unit is second) as follows:

$$PT_c \sim U(8, 10), \tag{24}$$

$$PT_p \sim U(2, 3). \tag{25}$$

3. Numerical test

In this section, we simulate each child's and each adult's movements in the scenario (see Figure 2) during the after-class period. First, we give the following initial conditions and assumptions:

(1) If $P_w(t_n) > 16$, PS is still a piecewise function that is positively correlated with $P_w(t_n)$.
(2) $\alpha_a = \beta_a = \alpha_c = \beta_c = 1$, $\varepsilon_a = 3, \varepsilon_c = 2$
(3) $\gamma_c = \begin{cases} 0, \text{ before the pick} - \text{up process} \\ 1, \text{ after the pick} - \text{up process} \end{cases}$
(4) If one pedestrian reaches around the classroom door at t_n, he/she will occupy the classroom door at t_{n+1} if possible.

Figure 4. Two screenshots of one round field video experiment, where (a) is the initial state and (b) is one middle screenshot.

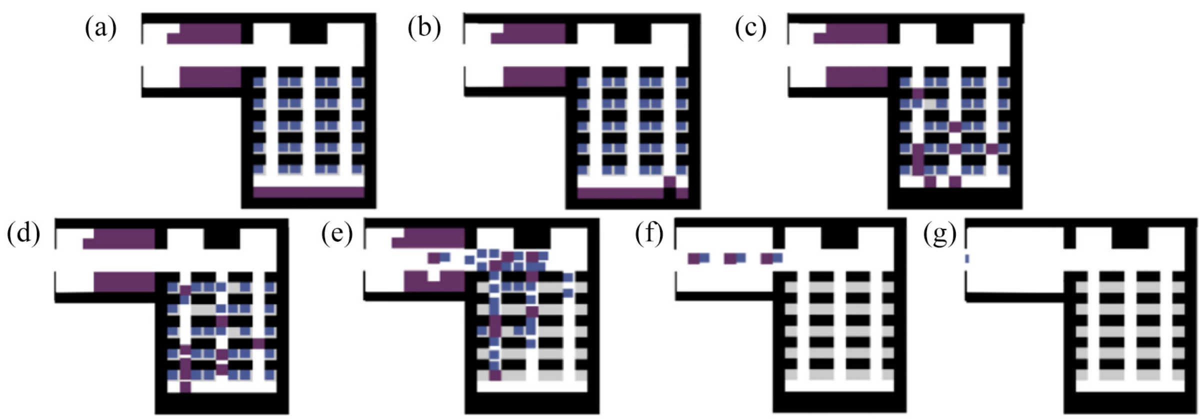

Figure 5. The whole evacuation process during the after-class period, where the time steps in (a)–(g) are 0, 5, 21, 22, 42, 194, and 204, respectively.

(5) The Nos. of the adults in the corridor are 1–21 and the Nos. of the adults in the classroom are 22–30; and the No. of the *i*th adult's child is i.

First, we explore the evacuation process during the after-class period (see Figure 5), where the blue squares and the dark red squares respectively represent children and adults. From Figure 5, we have:

(1) At the 0 time step, each pedestrian lies in his/her initial position.
(2) At the fifth time step, the first adult in the classroom leaves his/her seat and walk toward his/her child; he/she finishes the pick-up process at the 21st time step.
(3) At the 22nd time step, the first child leaves his/her seat and walks alone; he/she matches his/her child in the corridor at the 42nd time step.
(4) At the 194th time step, the last adult–child pair arrives at the door; they reach the exit at time step 204.
(5) Comparing with the adults in the corridor, the evacuation time of the adults in the classroom is longer, where the reasons are as follows: (i) the distances that the adults walk are longer, and (ii) the adults may meet conflicts with children and avoid the collisions.

Thus, we should explore the number of time steps that children and adults walk during the after-class period, where the number of time steps for the *i*th child and the *i*th adult are defined as $TL_{\mathrm{c}}^{\mathrm{i}}$ and $TL_{\mathrm{a}}^{\mathrm{i}}$, respectively. Figure 6 displays the simulation results, where the yellow and purple stems are respectively those of adults and children whose Nos. are 1–21 (i.e., the adults whose Nos. are 1–21 stay in the corridor), and the blue and orange stems are respectively those of adults and children whose Nos. 22–30 (i.e., the adults who Nos. are 22–30 stay in the classroom). As for $TL_{\mathrm{c}}^{\mathrm{i}}$ and $TL_{\mathrm{a}}^{\mathrm{i}}$, we cannot conclude some exact results, but obtain $\overline{TL_{\mathrm{a}}^{\mathrm{cl}}} > \overline{TL_{\mathrm{a}}^{\mathrm{co}}}$ and $\overline{TL_{\mathrm{c}}^{\mathrm{cl}}} > \overline{TL_{\mathrm{c}}^{\mathrm{co}}}$, where $\overline{TL_{\mathrm{a}}^{\mathrm{co}}}, \overline{TL_{\mathrm{c}}^{\mathrm{co}}}$ are the average values of $TL_{\mathrm{a}}^{\mathrm{i}}, TL_{\mathrm{c}}^{\mathrm{i}}(\mathrm{i} = 1, 2, \cdots, 21)$, respectively, and $\overline{TL_{\mathrm{a}}^{\mathrm{cl}}}, \overline{TL_{\mathrm{c}}^{\mathrm{cl}}}$ are the average values of

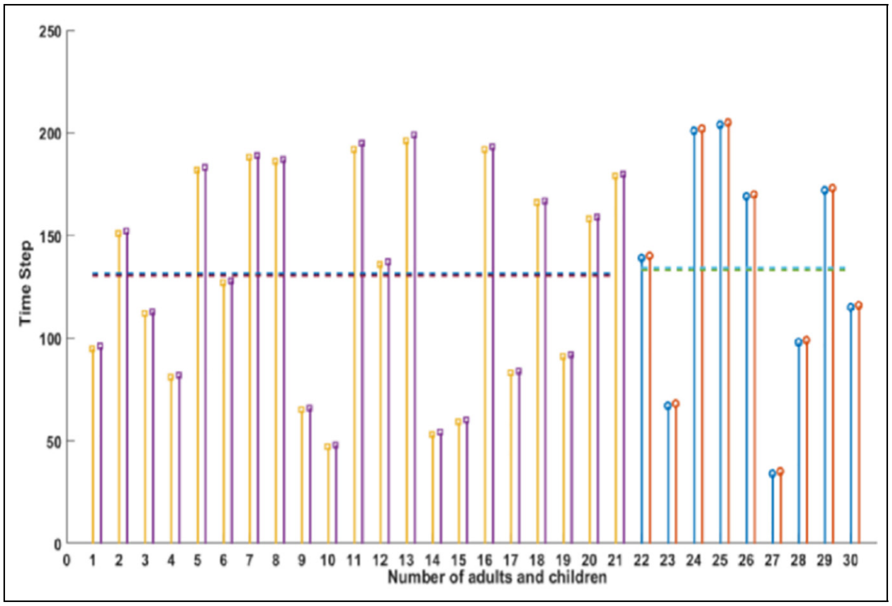

Figure 6. The number of time step for each pedestrian and the corresponding average values for children and adults.

$TL_a^i, TL_c^i (i = 22, 23, \cdots, 30)$, respectively. Randomness exists when each pedestrian makes route choice, but the average values of $\overline{TL_a^{cl}}$, $\overline{TL_a^{co}}$ ($\overline{TL_a^{cl}} > \overline{TL_a^{co}}$) and $\overline{TL_c^{cl}}$, $\overline{TL_c^{co}}$ ($\overline{TL_c^{cl}} > \overline{TL_c^{co}}$) can reflect the avoidance behavior of the adults in the classroom to other children. To be specific, for the adults in the classroom, when they face the situation of competing with other children during the movement process, they will choose to wait and avoid. This avoidance may lead to a chain reaction, that is, an adult in the classroom will keep waiting until all the other children competing with him/her for the same position pass. Therefore, it can be seen that some adults in the classroom continuously avoid children, that is, the corresponding TL_a^i continuously increases and $\overline{TL_a^{cl}} > \overline{TL_a^{co}}$.

All the adults in the classroom walk to their children's positions and finish the matching process, so their children have no searching behaviors or acceleration behaviors before matching. After matching, the children's behaviors are similar to those of other children. Hence, we only study the behaviors of other children and their adults in the corridor since the above two behaviors do not occurs in the classroom. Based on the discussions in Section 2, we can divide the behaviors of the adult–child pairs (formed in the corridor) into child's searching behavior at the classroom door, child's acceleration behavior under possible conditions, adult's leading behavior, child's following behavior, and the synchronized movement of adult–child pair. Here, we should only provide an adult–child pair's behaviors in Figure 7 (here, the time step (that the child arrives at the classroom door) is set as 0 and then counted), and this adult–child pair is the first adult–child pair formed in the matching area with $P_w(t_n) = 21$. In Figure 7, the yellow line includes two segments that denote the child's searching behavior at the classroom door and his/her acceleration behavior when he/she enters the matching area; the blue line denotes that the adult enters the matching area and finishes the matching process; the red line and the purple line denotes the child's following behavior, the adult's leading behavior and their synchronized movements; and the green line denotes the distance between the adult and his/her child after the adult enters the matching region. From Figure 7, we can draw the following conclusions:

(1) The child's searching time at the classroom door is about 12 time step, that is, it is about 5 s. The maximum value of $P_w(t_n)$ for the designed experiment was 16, which is less than $P_w(t_n) = 21$ in this case. Therefore, the corresponding PS is larger than the maximum PS value shown in Equation (15). As shown in Equation (15), PS is a piecewise function related to $P_w(t_n)$, and it increases monotonically with the increase of $P_w(t_n)$. Therefore, in the case of $P_w(t_n) = 21$, $PS = 12$ is reasonable and consistent with Equation (15).
(2) Before matching, the child accelerates for two time steps since the current traffic states around this child allow him/her to accelerate.
(3) The matching time is one time step, which shows that the matching speed is very fast.
(4) During the matching process, the distance between the adult and his/her child drops to four walk step, where the initial distance is five walk step that is accordant with the results of questionnaire surveys. After matching, the distance is four walk step, which shows that the adult's leading

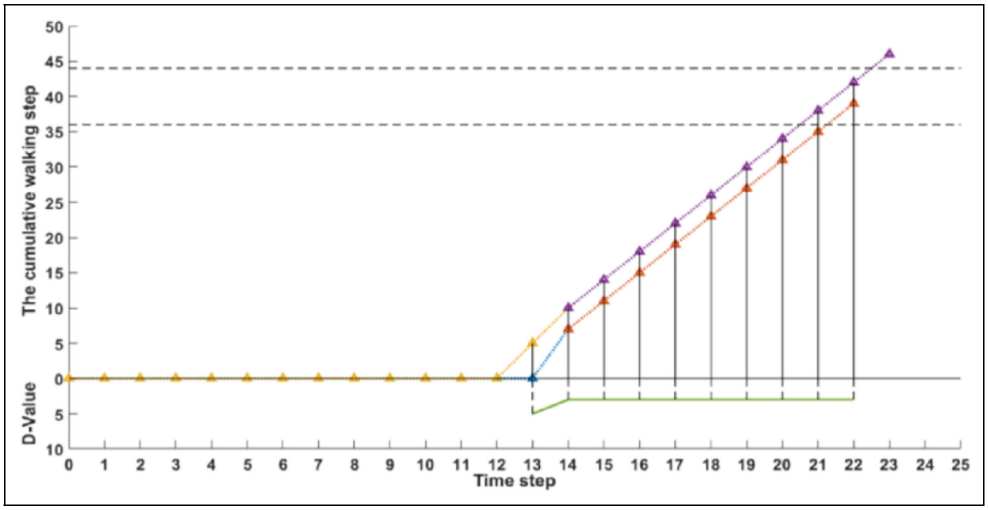

Figure 7. The number of walk steps of one adult–child pair and the distance between the two pedestrians during the after-class period.

behavior, the child's following behavior, and their synchronized movement exist.

In the above simulations, each pedestrian's behaviors (e.g., matching behavior) are self-organized, and some initial conditions (e.g., each child's position in the classroom) are randomly set, so the evacuation efficiency may be relatively low. As for training schools, the administrators care the operational efficiency and the safety, so we should study how to enhance the evacuation efficiency during the after-class period. Thus, we propose some strategies to achieve the goals. Before proposing the strategies, we should give the following notes:

(1) Each strategy is focused on an aspect that can be easily optimized and used by pedestrians during the after-class period.
(2) Each strategy involves the features of pedestrian movement and the management of training school and is feasible.
(3) Under each strategy, each pedestrian's movement is still in line with the reality during the after-class period.
(4) (4) If one strategy is too conditional or restrictive for the application, the cooperation degree of adults and children may be low, and it is hard to practice in a real-life case.

In fact, if some adults' chairs are not properly arranged, there exists bidirectional flow in the yellow region as shown in Figure 8. At this time, the time and the walk distance that some adults reach their children's position increase. If the ith adult can select a proper chair and help his/her child to pack belongings when he/she arrives at

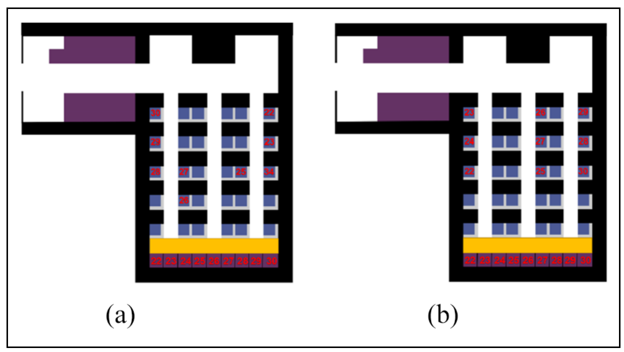

Figure 8. Two arrangements for adults' chairs, where (a) and (b) correspond to the cases without strategy and under Strategy I, respectively.

his/her child's position, PU_i and the walk time of this adult in the classroom drops. As for the adults' chairs, we define two arrangements, where the first case is that each adult's chair is randomly distributed while the second case is that each adult's chair is arranged based on his/her child's chair (see Figure 8). Here, we define the two cases as "without strategy" and Strategy I, respectively. Next, we study the numbers of each adult's walk steps in the classroom (see Figure 9), and the numbers of occurrence of bidirectional flow in the yellow region (see Figure 10) under the two cases. Figure 9 shows that the number of each adult's walk steps drops under Strategy I, and Figure 10 shows that Strategy I can completely eliminate bidirectional flow in the yellow region. This shows that Strategy I can both enhance the evacuation efficiency and the safety in the classroom.

Besides the above strategies in the classroom, we propose some strategies in the corridor to enhance the

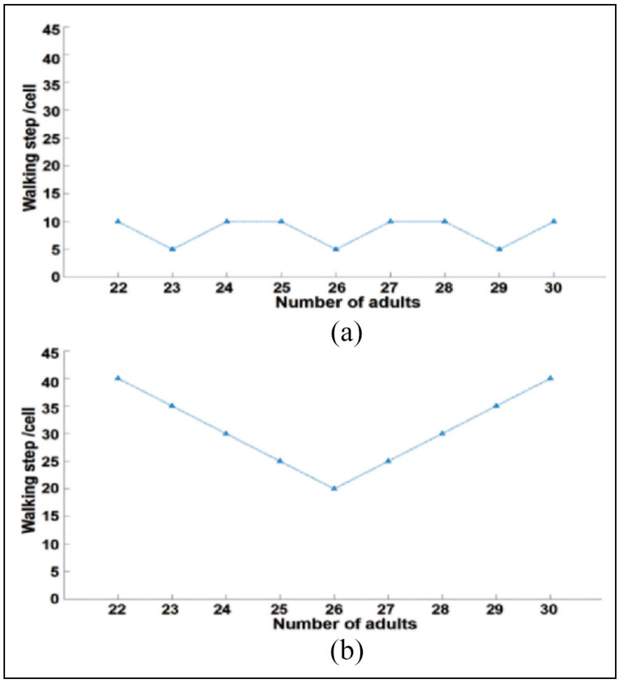

Figure 9. The numbers of each adult's walk steps in the classroom under the two cases, where (a) and (b) are those without strategy and under Strategy I, respectively.

evacuation efficiency of training school during the after-class period. The questionnaire surveys show that most pedestrians tend to walk along the corridor center without guidance. This behavior may cause congestion, so we should guide each pedestrian to walk along one side of corridor if possible. This guidance is defined as Strategy II. The number of each cell occupied by pedestrians and the total evacuation time can be used to evaluate the impacts of Strategy II on the evacuation efficiency, so we study the two indexes without guidance and under Strategy II (see Figure 11). To highlight the impacts of Strategy II on the above two indexes, the simulation results without guidance are listed in Figure 11. From Figure 11, we obtain the following findings:

(1) The number of times that the center cells in the corridor and at the classroom door are occupied are very high without strategy (i.e., they are much greater than those at the two sides of the door and the corridor); but they sharply decrease under Strategy II and the number time of each cell occupied becomes relatively uniform, which shows that this strategy can enhance the safety in the corridor.
(2) The total evacuation time without guidance is much greater than the one under Strategy II, which shows that Strategy II can enhance the evacuation efficiency.

In several simulations where the relative initial positions of adults and their children in the classroom are not optimized under some specific cases, the initial positions of adults and the corresponding children in the classroom are randomly assigned. And the simulation results indicate that each strategy is effective since it can enhance the evacuation efficiency (some strategies can also enhance the safety). However, we do not combine two or more strategies to study the evacuation process at the scenario shown in Figure 2 due to the following reasons:

(1) Too random factors exist in the scenario.
(2) Applying multistrategies is very difficult to explicitly display the effects of each strategy on the evacuation process.

4. Conclusion

Many CA models have been developed to study the pedestrian flow at some public places (e.g., supermarket, classroom, etc.), but the models cannot be used to depict each pedestrian's movement at a training school since the

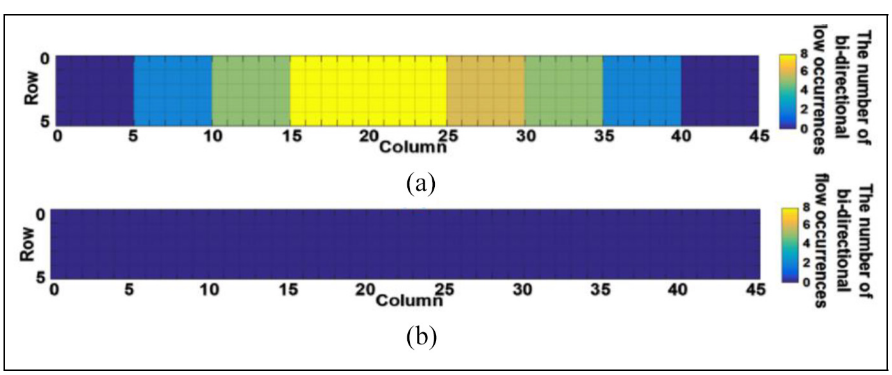

Figure 10. The numbers of occurrence of bidirectional flow steps in the yellow region, where (a) and (b) are those without strategy and under Strategy I, respectively.

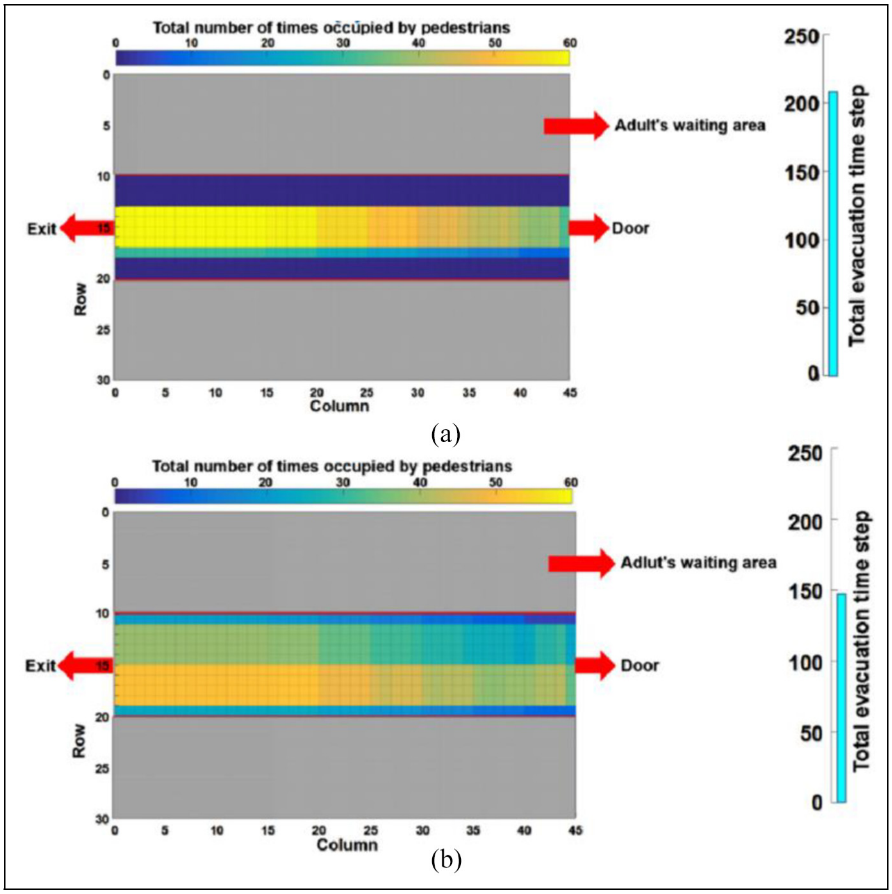

Figure 11. The number of times occupied by pedestrians at each feasible cell, and the total evacuation time, where (a) and (b) correspond to the results without guidance and under Strategy II, respectively.

pedestrian flow consists of adults and children. To study this topic, Tang et al.[17,18] developed two CA models to describe each pedestrian's movement in a training school classroom and the adult–child matching behavior in the matching area during the after-class period, but did not consider the movement difference between adult and child, so the two CA models cannot perfectly describe the pedestrian flow at a training school, yet. In this paper, we design some questionnaire surveys to extract some basic features of adult's and child's movements, propose a fine grid CA model, estimate/calibrate some parameters based on some video data, and use the calibrated model to study each pedestrian's movement and the corresponding phenomena occurring in the training school classroom and in the corridor during the after-class period. In addition, we propose four strategies to study the evacuation efficiency in the tested scenario during the after-class period.

However, this paper still has the following limitations:

(1) The number of effective questionnaire surveys is too small.
(2) Due to the actual conditions, the adults in the video are replaced by volunteers, which may cause some errors in the data calibration.
(3) We do not consider the case that some adults may pick up two or more children.

In view of the above limitations, in the future study, we will carry out more experiments and collect more data to extract various basic features of the pedestrian flow at training schools, and then propose a more realistic CA model to explore the heterogeneous pedestrian flow during the after-class period. Besides, more participants should be involved to get more data for reliable statistical analysis of parameter's estimation. If considering the whole school with multi-classrooms, some behavioral, psychological, and physical heterogeneities among children (e.g., different age groups) need to be considered.

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ORCID iD

Tie-Qiao Tang https://orcid.org/0000-0003-3730-0819

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Appendix 1

First, we introduce the adult's questionnaire surveys, which include the following eight questions:

Q1: If the respondent walks alone, how far apart from the pedestrian in the movement direction does he/she walk (see Figure A1(a))?
Q2: If the respondent leads a child, how far apart from the pedestrian in movement direction will he/she walk (see Figure A1(b))?
Q3: When the forward space is large enough under Q1, does he/she accelerate (see Figure A2(a))?
Q4: When the forward space is large enough under Q2, does he/she accelerate (see Figure A2(b))?

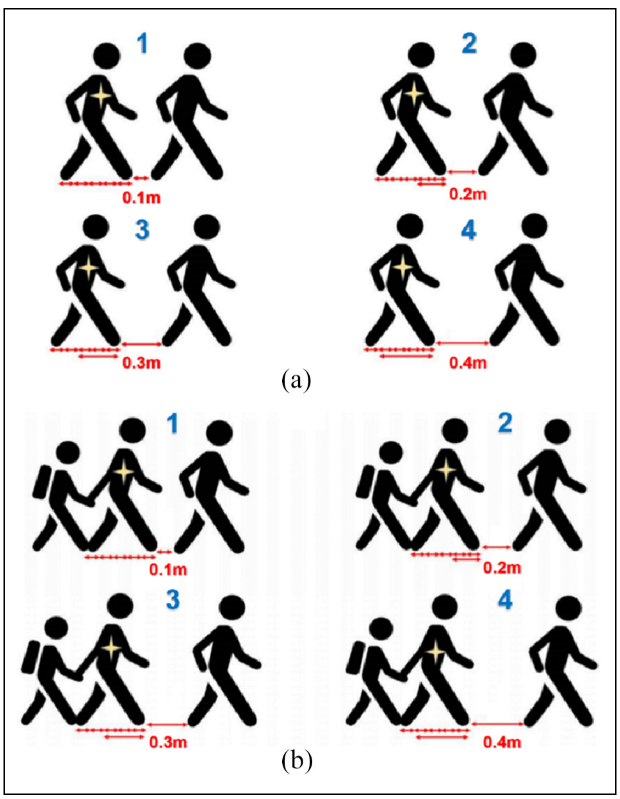

Figure A1. Schematic diagrams of Q1 and Q2, where (a) is Q1 and (b) is Q2.

Q5: When the respondent can select Path a, b, or c (see Figure A3), which path does he/she select? Here, Path a or c shows that the respondent keeps to the side, where the available space at his/her current position is large enough on Path a, and the situation near his/her current location is relatively congested on Path c; Path b shows that he/she walks along the center line.
Q6: How does the respondent in the classroom pick his/her child up? This question includes three options, that is, (a), (b), and (c), where (a) is that the respondent walks to his/her child's desk, (b) is opposite to (a), and (c) is that the respondent and his/her child meet outside classroom.
Q7: Does the respondent avoid child when competing the same position with a child?
Q8: Does the respondent run across the gap between the desk and chair? This question has case (a), (b), and (c), where case (a) shows that there is no pedestrian near the target position, case (b) shows that one pedestrian stays at the target position, and case (c) shows that there is no pedestrian at the target position, but one pedestrian moves toward the target position (see Figure A4). Note: the respondent selects (a)–(c) shows that this adult will run across the gap; otherwise this adult does not run across the gap.

Next, we introduce the child's questionnaire surveys, which includes the following seven questions:

Q9: This question is the same as Q1 (see Figure A5(a)), but we need only list three options.
Q10: Under Q9, does the respondent accelerate if the available space is enough (see Figure A5(b)).
Q11: This question is the same as Q5.
Q12: This question is the same as Q6.
Q13: This question is the same as Q8, but it has cases (d)–(h) besides the three cases in Q8 (see Figure A6). Case (d) indicates that one child stays at the gap between desk and chair when the respondent is running across the gap; cases (e)–(h) are respectively similar to cases (a)–(d) but show that the respondent runs across multisuccessive gaps. Like Q8, if the respondent selects (a)–(d) (or (e)–(f)), it shows that he/she runs across the gap (or multisuccessive gaps), otherwise he/she does not run across any gap.

As for the questionnaire surveys, we need give the following notes:

(1) The scenario is a nonemergency indoor evacuation.

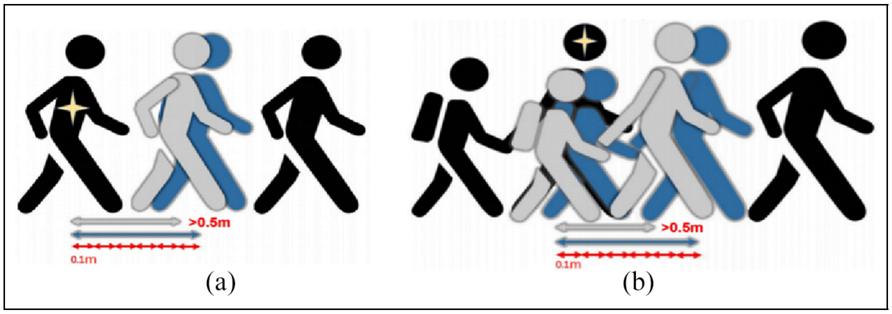

Figure A2. Schematic diagrams of Q3 and Q4, where (a) is Q3 and (b) is Q4.

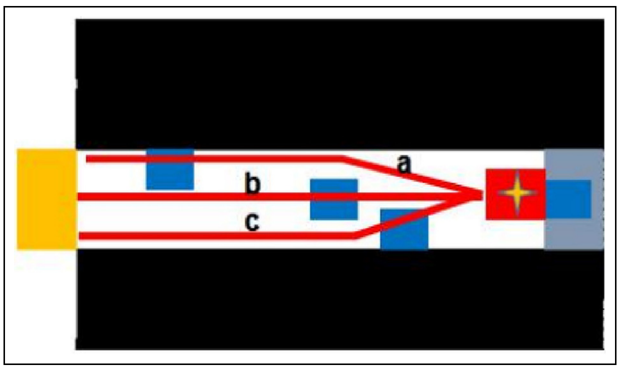

Figure A3. Schematic diagram of Q5.

(2) Lei et al.[26] pointed out that the child's and adult's space sizes can respectively be defined as 0.4 m × 0.4 m and 0.5 m × 0.5 m, and that each pedestrian's walk pace is positively correlated with his/her shoulder width. For simplicity, we can respectively set the child's and adult's walk paces as 0.4 m and 0.5 m, that is, each adult chooses (1), (2), (3), or (4) if the gap is not less than 0.1 m, 0.2 m, 0.3 m, or 0.4 m; the critical values in Q3 and Q4 are defined as 0.5 m; each child chooses (1), (2), or (3) if the gap is not less than 0.1 m, 0.2 m, or 0.3 m; the critical values in Q10 is defined as 0.5 m.

We asked 200 adults and 200 children in Shenzhen New World Training School to conduct the questionnaire survey, and received 192 valid questionnaire surveys for adults and 179 valid ones for children. The oldest and youngest children are 11 and 7, respectively, and the child's average age is 8.9; but we cannot provide the adult's average age because most adults did not fill the option.
Generally speaking, adults have higher rationality and more comfort requirements for a walk, so they prefer to keep the walking pace and a certain distance from their adjacent pedestrians. Qiang et al.[34,35] introduced some related factors into the pedestrian's following behavior and studied the effects of the factors on the aircraft boarding efficiency. When adults lead their children to walk, they will walk more cautiously (e.g., adjusting their walk speed to meet children's walk speed). Although most children use safe walk strategy (e.g., they do not get too close to other pedestrians or walk too fast), some may accelerate

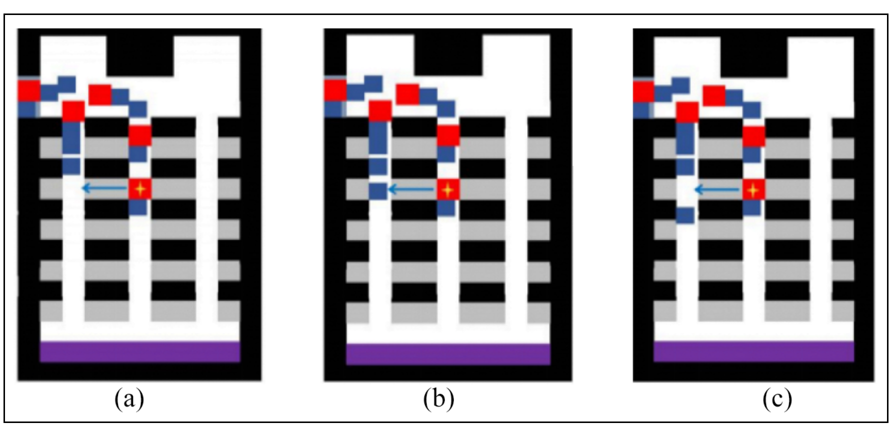

Figure A4. Schematic diagram of Q8.

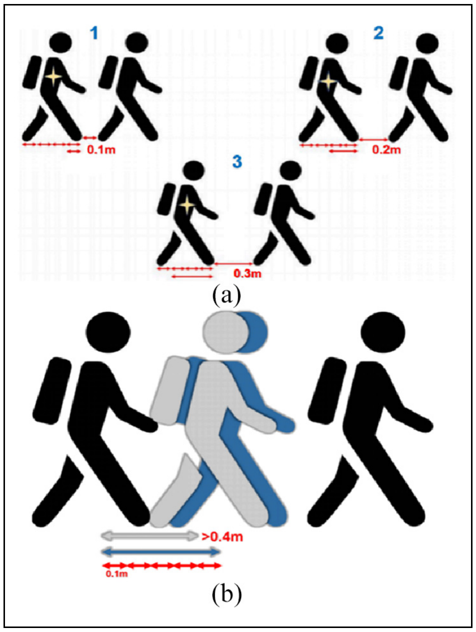

Figure A5. Schematic diagrams of Q9 and Q10, where (a) is Q9 and (b) is Q10.

or approach other pedestrians due to low rationality. From the valid questionnaire surveys, we can summarize the following qualitative features of pedestrian flow at the training school:

(1) As for alone adults, they walk when the shortest distance between them and their front pedestrian is 0.3 m; as for the adults leading one child, the shortest distance is 0.4 m; as for alone children, the shortest distance is 0.2 m.
(2) When walking alone and leading a child, adults do not accelerate; when walking alone, some children accelerate if possible.
(3) Adults and children choose the path in the center line of corridor since this path is wider and uncongested.
(4) Adults walk to their children's position and leave the classroom together with their children.
(5) Adults do not run across Θ; some children run across Θ when the target position is empty while the current position in their movement direction is occupied by a pedestrian; some children may run across multisuccessive Θ if possible.
(6) Adults avoid other children if some conflicts between them and children occur. Note: adults do have this avoiding behavior in the training school classroom during the after-class period. Most pedestrians have low walking freedom, strong self-interest, and strong aggressiveness under the situations of high-density pedestrian flow and emergency evacuation, but each adult will consider other children's security and avoid other children in the tested scenario during the after-class period if some conflicts occur between him/her and other children.

As for the questionnaire survey, we should give the following notes:

(1) The picture-based questionnaire surveys are easy to understand even for children. It has a good performance (especially in the study of the features of child's movement).[36]
(2) The video surveys to explore such complicated behavior may cause some tough privacy and safety issues, but some features of children's and adult's movements can be also extracted by questionnaire. To reproduce the behaviors of pedestrians at the training school as real as possible, the surveys should involve adults and children.
(3) The results of the questionnaire survey may have some accuracy problems, which have some quantitative impacts on the simulation results, but the aim of this paper is to study each pedestrian's movement behavior and the corresponding complex phenomena in the tested scenario during the after-class period. Hence, considering the pros and cons of the above questionnaire survey, the negative effect of this method can qualitatively be acceptable.

Appendix II

As for the questionnaire surveys of pedestrian flow, researchers[36,37] have done some statistical analyses. But since the statistical analyses of the questionnaire surveys two are beyond the scope of this paper, we introduce them in detail as follows:

(1) As for alone walk, the numbers of adults walking at the distance larger than or equal to 0.4 m, 0.3 m, and 0.2 m from the front pedestrian are 70 (36.4%), 119 (62.0%) and 3 (1.6%), respectively; but when leading one child, the numbers of adults walking at the distance greater than or equal to 0.4 m, 0.3 m, and 0.2 m are 176 (91.7%), 13 (6.7%), and 3 (1.6%), respectively. Because each child walks alone, the numbers of children walking at a distance greater than or equal to 0.3 m, 0.2 m, and 0.1 m from the front pedestrian are 12 (6.7%), 138 (77.1%), and 29 (16.2%), respectively.
(2) When enough empty cells exist in the walk direction under alone walk: 186 adults (96.9%) and

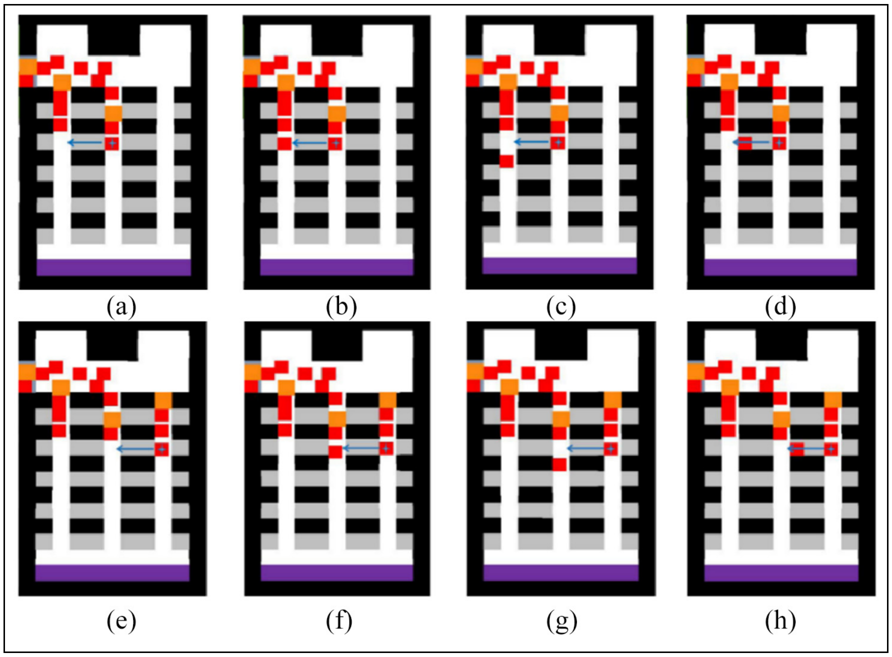

Figure A6. Schematic diagram of Q13.

189 adults (98.4%) do not accelerate, whereas 57 children (31.8%) will accelerate.

(3) In a wider and uncongested corridor, 188 (97.9%) adults and 169 children (94.4%) walk along the corridor center.

(4) During the after-class process: 188 (94.8%) adults first pick their children up at their children's initial positions and then walk together; 154 (86.0%) children wait for their adults at their initial positions.

(5) For Figure A4(a)–A4(c), the numbers of adults who run across the Θ are 7 (3.6%), 2 (1.0%), and 4 (2.1%), respectively, and 179 (93.3%) adults do not run across the Θ; for Figure A6(a) –A6(h), the numbers of children who run across the Θ are 62 (34.6%), 61 (34.1%), 61 (34.1%), 8 (4.5%), 62 (34.6%), 60 (33.5%), 61(34.1%), and 8 (4.5%), respectively. About 189 adults (98.4%) avoid children when conflicts occur between an adult and a child.

Appendix III

All the children lie in the same research scenario in this paper, so we can assume that they have the same features (i.e., they can be regarded as a population). Therefore, for the estimation of p_c^{ac}, we can prove that the acceleration proportion of children in the sample (i.e., $\overline{p_c^{ac}}$) is an unbiased estimation in the population (i.e., $\overline{P_c^{ac}}$), where the proof is as follows:

(1) Assuming that the total number of children is N, the accelerated choice behaviors form a set $\{(p_c^{ac})_1, (p_c^{ac})_2, ..., (p_c^{ac})_N\}$. If the ith child chooses to accelerate, $(p_c^{ac})_i = 1$; otherwise, $(p_c^{ac})_i = 0$. The population mean value can be described as $\overline{P_c^{ac}} = \frac{1}{N}\sum_{i=1}^{N}(p_c^{ac})_i$.

(2) Sampling $\{(p_c^{ac})_1, (p_c^{ac})_2, ..., (p_c^{ac})_N\}$, the sample is the acceleration behavior data of children collected in this study; the sample size is NQ_c. The sample mean value can be described as $\overline{p_c^{ac}} = \frac{1}{NQ_c}\sum_{i=1}^{NQ_c}(p_c^{ac})_i\delta_i$. δ_i is the sampling function and can be described as $\delta_i = \begin{cases} 1, \text{if}(p_c^{ac})_i \text{isselected} \\ 0, \text{otherwise} \end{cases}$, with $\sum_{i=1}^{N}\delta_i = NQ_c$.

(3) Setting $H = \sum_{i=1}^{N}(p_c^{ac})_i\delta_i$, we have

$$E(H) = \frac{NQ_c! \cdot (N - NQ_c)!}{N!} \cdot \frac{(N-1)!}{(N-NQ_c)! \cdot (NQ_c - 1)!} \cdot \sum_{i=1}^{N}(p_c^{ac})_i, = \frac{NQ_c}{N} \cdot \sum_{i=1}^{N}(p_c^{ac})_i \tag{A1}$$

$$E(\overline{p_c^{ac}}) = E\left(\frac{H}{NQ_c}\right) = \frac{1}{N} \cdot \sum_{i=1}^{N}(p_c^{ac})_i = \overline{P_c^{ac}}. \tag{A2}$$

Thus, the acceleration proportion of children in the sample is an unbiased estimation in the population.

For the estimation of p_c^{ac}, The proof that crossing proportion of children in the sample (i.e., $\overline{p_c^{cr}}$) is an unbiased estimation in the population (i.e., $\overline{P_c^{cr}}$) and can be done by the same method.

Author biographies

Chuan-Zhi Xie received BEng degree in transportation engineering in 2018 from the School of Transportation Science and Engineering, Beihang University, Beijing, China. Currently, he is a PhD Candidate at the School of Transportation Science and Engineering, Beihang University, and a Visiting Scholar at the Université Claude Bernard Lyon 1, France. His research mainly focuses on pedestrian flow dynamics.

Tie-Qiao Tang is currently a Professor at the School of Transportation Science and Engineering, Beihang University, Beijing, China. He has authored or co-authored more than 150 SCI-indexed papers in Transportation Research Part C & D, Physical Review E, Nonlinear Dynamics, etc. His works receive more than 5300 citations and his H-index is 45 (Google Scholar Database). He now serves as an associate editor for Transportmetrica A. His research interests include traffic flow modeling, crowd emergency management, air transportation management, etc.

Bo-Tao Zhang received a BE degree and an ME degree in traffic and transportation engineering from Beihang University, Beijing, China, in 2018 and 2021, respectively. He will start his PhD research in the Department of Civil and Architectural Engineering at the City University of Hong Kong in September 2021. His research interests include modeling and simulation of pedestrian flow, large-scale building evacuation risk analysis, and optimization for evacuation planning.

Heng-Jun Xiang is currently the chairman of Shenzhen New World Training Co., Ltd. From 1995 to 2004, he was awarded the titles of "Shenzhen education advanced worker" and "Shenzhen outstanding contribution award for teaching". In 2005, he was rated as the "excellent educator in Shenzhen"; in 2008, he was rated as the "leader of Shenzhen education" by Shenzhen media; in 2009, he was rated as the "top figure of Shenzhen education".