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A study of pedestrian group behaviors in crowd evacuation based on an extended floor field cellular automaton model

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ABSTRACT

In the study of pedestrian movements, a consideration of group behaviors is important because of their potential impacts on pedestrian flow dynamics. In this paper, we investigate the group behaviors during emergency evacuation, which is a critical case for emergency crowd management but has not been fully explored and understood. It has been well recognized that in evacuation situations, some people within a crowd, especially those who are with families and friends, often move in small groups and act in particular patterns distinct from individuals. As a result, the crowd is a mixture of individuals and groups rather than a pure collection of individuals. To capture and evaluate the influence of group behaviors on crowd evacuation, we propose an extended floor field cellular automaton (CA) model that takes into account such phenomena. Our model is formulated by leveraging the leader-follower behavior rule that is evident in pedestrian group behaviors. To calibrate and validate the proposed model, a few field experiments of crowd evacuation were conducted in a university building. Through a representative case study, it is demonstrated that the proposed extended floor field CA model can replicate the well-known phenomena in crowd evacuation such as collective arch-like clogging at the exit as well as other commonly observed group behaviors in evacuation. Moreover, it is found that the total crowd evacuation time significantly increases with the presence of pedestrian groups in the crowd. The results also show that such negative effects of group behaviors in crowd evacuation intensify when the density of the crowd is higher. Subsequently, sensitivity analyses are performed to further explore how pedestrian group behaviors are influenced by model parameters that reflect the pedestrian flow dynamics in evacuation scenarios. With its capability of realistically replicating the field pedestrian evacuation, the proposed model can serve as a valuable tool for predicting crowd evacuation time and designing guidelines for pedestrian evacuation in emergency situations, in particular when group behaviors are salient.

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1. Introduction

Recently, the simulation models of pedestrian dynamics have been widely utilized by researchers in certain research fields including evacuation planning (Helbing et al., 2001, 2007; Richter et al., 2013; Schadschneider et al., 2009), evacuation infrastructure deployment (Shiwakoti and Sarvi, 2013) and optimization of public transport operations (Abdelghany et al., 2014; Helbing et al., 2005; Shiwakoti et al., 2009). A prerequisite to realizing these applications is that the simulation models should be able to represent and replicate realistic pedestrian behaviors. Over the past few decades, various approaches have been proposed to simulate crowd evacuation including fluid dynamics models (Henderson, 1971, 1974), gas-kinetic models (Agnelli et al., 2015; Degond et al., 2013; Hoogendoorn and Bovy, 2000), social force model (Anvari et al., 2015; Helbing and Molnar, 1995; Henderson, 1971), cellular automaton model (Jian et al., 2014; Xiao et al., 2016; Yu and Song, 2007), agent-based model (Farhan, 2015; Wang et al., 2014, 2016; Yin et al., 2014), network-based model (Kunwar et al., 2016; Løvås, 1994). In general, these models can be classified into continuous and discrete models. Compared with the discrete models, the continuous models are more sophisticated in terms of representing pedestrian behaviors, whereas they are more computationally intensive to simulate complicated geometries and large-scale scenarios (Guo and Huang, 2012).

The demand of high computational efficiency can be well alleviated by using the classical cellular automation (CA) model, which allows for large-scale computer simulations due to its discrete property (Abdelghany et al., 2016). The CA model creates an approximation of actual individual behavior with simple local rules. It has been proven that the CA model is capable of replicating sophisticated pedestrian motions and reproducing a variety of pedestrian dynamics phenomena such as lane formations in bi-direction pedestrian flow and jamming and clogging in dense crowds (Kuang et al., 2008; Ma et al., 2010; Xiao et al., 2016; Zhang, 2015). However, although the CA model has many merits, it cannot well represent pedestrian's walking behavior since it is formulated on the basis of discrete space and time. Specifically, in the CA model, a pedestrian looks like a hopper that jumps from one lattice to another. Consequently, the more complex collective phenomena of pedestrian flows such as oscillation patterns at intersections or freezing-by-heating cannot be replicated with the CA model.

As the extensions of the classical CA model, a variety of CA-based models for pedestrian flow simulations have been proposed over the last decade such as the Blue and Alder CA model (Blue and Adler, 2000, 2001), the floor filed CA model (Burstedde et al., 2001; Kirchner and Schadschneider, 2002; Kirchner et al., 2003). Most of these CA models treat pedestrians in a crowd as homogeneous individuals. However, it is well known and generally recognized that pedestrian crowds are often a mix of individuals and groups. The existing empirical and observational studies have shown that pedestrian groups account for a large proportion of crowds in walking areas and the group behaviors significantly affect crowd dynamics (Moussaïd et al., 2010). After recognizing this phenomenon, some researchers have tried to incorporate the group behaviors when developing a reliable pedestrian simulation model. Moussaïd et al. (2010) extended a general social force model by introducing an interaction force within group members and successfully simulated group spatial patterns at different pedestrian density levels. Other existing models for pedestrian group behavior were mainly based on the behavior rule that group members were likely to stay close to each other and keep a certain spatial structure (Bandini et al., 2011; Köster et al., 2011; Qiu and Hu, 2010; Reynolds, 1987; Vizzari et al., 2013). These studies have demonstrated that pedestrian groups act in a way distinct from isolated individuals and have a meaningful impact on crowd dynamics. However, few studies have addressed the modeling of pedestrian group behaviors in emergency evacuation, a most critical scenario among all use cases.

Evacuation often occurs at places where people gather to live, work, study or entertain. As pointed out in an early literature that crowds were often dominated by small groups at large events (James, 1953), it is reasonable to deduce that a significant portion of a crowd is likely to act in groups during evacuation, in particular when they evacuate with families and friends. In addition, according to some empirical investigations, the pedestrian group behaviors in evacuation are quite different from those in normal situations. Specifically, pedestrians in groups tend to stay close to each other and choose the same egress to exit during evacuation. The behavior of backtracking often occurs when a pedestrian realizes that his or her partners are lost. However, a majority of existing models for group movements in evacuation did not fully account for these group behavioral characteristics. For example, while Xu and Duh (2010) modeled the pedestrian group behavior in evacuation by introducing the bond force to reflect the fact that groups are tend to walk abreast in evacuation, their study didn't cover the aforementioned characteristics of pedestrian group behaviors, such as staying together or backtracking. Yang et al. (2005) studied the psychological effect of being with a crowd and the kin behavior inside the crowd by simulating a two-dimensional CA model. However, their study mainly focused on the descriptive analysis of the psychology and lacked a detailed description of lacked a detailed specific description on its simulation model approach.

To address the deficiency in the previous studies and to enhance the understanding of crowd dynamics in evacuation, the primary objective of our work is to develop a reliable simulation model that takes into consideration all these important characteristics of group behaviors. In this paper, an extended floor filed CA model is proposed to model the group behaviors in pedestrian evacuation. The main idea of the typical floor filed CA model is based on bionics that aims to capture pedestrians' herding behaviors, as well as the behaviors of seeking the shortest path in the evacuation process (Kirchner and Schadschneider, 2002). The model has been successfully used in previous studies to investigate pedestrian evacuation dynamics (Hsu and Chu, 2014; Jian et al., 2014). The formulation of such a model is flexible and extensible to incorporate additional social and psychological factors for crowd evacuation simulation (Bandini et al., 2014; Duives et al., 2013). However, the general floor field CA model hasn't been extended to incorporate the pedestrian group behavior in crowd evacuation, which is the main contribution of our work reported here.

In this paper, we will describe how to explicitly incorporate the characteristics of pedestrian group behaviors into a general floor field CA model. This extended floor field CA model with group behaviors are calibrated and validated with a few field evacuation experiments conducted in a university building. The results show that the proposed model can accurately predict the evacuation time and well reflect the collective phenomenon observed empirically. More importantly, noticeable pedestrian group behaviors are captured by this simulation model to show their significant impact on the evacuation process. Thereby, we successfully verify that the pedestrian groups constitute a crucial component of the evacuation crowds.

The rest of this paper is organized as follows. The next section provides a brief description of the floor field model and discusses the innovative improvements we made in a general floor filed CA model to capture the group behaviors. Section 3 describes the field experiments of pedestrian evacuation that are conducted to calibrate the proposed model. Then the simulation results based on the proposed model are compared with the observations obtained in a representative case study. Subsequently, a sensitive analysis of the model parameters is performed to further explore how pedestrian group behaviors are influenced by model parameters that reflect the pedestrian flow dynamics in evacuation scenarios. The conclusion section summarizes the observations of this study and discusses the benefits of utilizing the proposed model.

2. Model development

2.1. A brief introduction of the floor field CA model

The floor field CA model is constructed in a microscopic and discrete form, where pedestrians are allowed to move to one of its neighboring cells at each time step with certain probability determined by specific rules. The traditional floor field model is inspired by the phenomenon of chemotaxis (Kirchner and Schadschneider, 2002). Denote $S_{i,j}$ as the static floor field and $D_{i,j}$ as the dynamics floor field. The static floor field $S_{i,j}$ describes the pedestrian's behaviors of finding the shortest path to egress while the dynamics floor field $D_{i,j}$ describes the pedestrian's behaviors of following other individuals during evacuation. Specifically, the static field describes the attractiveness of exits to pedestrian and is set inversely proportional to the distance from the exits, that is, the cell closer to the exit has relatively greater attraction. On the other hand, the dynamic floor field represents the virtual trace left by pedestrians. This corresponds to the phenomenon that people tend to follow others' traces, i.e., the herding behavior. The dynamic field is time-dependent and is modified according to the diffusion and decay rules. In each time step, the dynamic floor field at the original cell of each moving pedestrian increases by one. It decays with probability α and diffuses with probability δ to one of its neighboring cells. The Von Neumann neighborhood is adopted in this model as shown in Fig. 1 and the transition probability is calculated with the following equation:

$$P_{i,j} = N \exp(k_S S_{i,j}) \exp(k_D D_{i,j})(1 - \eta_{i,j})\varepsilon_{i,j} \tag{1}$$

where

$$\eta_{i,j} = \begin{cases} 0 & \textit{if the cell}(i,j) \textit{ is} \\ 1 & \textit{if the cell}(i,j) \textit{ is occupied} \end{cases}$$

$$\varepsilon_{i,j} = \begin{cases} 0 & \textit{the cell is forbidden (e.g. walls or obstacles)} \\ 1 & \textit{else} \end{cases}$$

To make the summation of transition probabilities of all neighboring cells equal to 1, the coefficient N is set as following:

$$N = \left[\sum \exp(k_S S_{i,j}) \exp(k_D D_{i,j})(1 - \eta_{i,j})\varepsilon_{i,j}\right]^{-1} \tag{2}$$

where k_S and k_D are the sensitivity parameters determining the weight of $S_{i,j}$ and $D_{i,j}$ respectively.

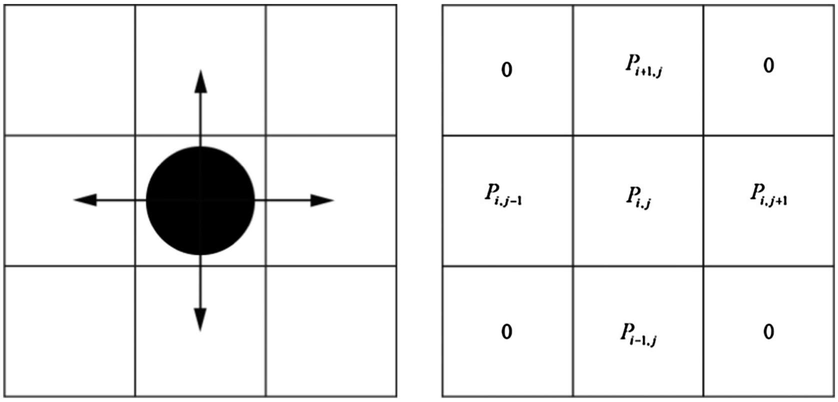


Fig. 1. Von Neumann neighborhood.

2.2. Modeling of pedestrian group behaviors

According to empirical studies, in normal situations the pedestrian groups tend to sustain a certain spatial pattern to facilitate communication and cohere with each other. The similar phenomenon can also be observed in evacuation since pedestrians are inclined to stay together to alleviate their nervousness and anxiety (Qiu, 2010). Another typical behavior of pedestrian group is backtracking, that is, pedestrians may turn back to search for their lost group members in evacuation (Bryan, 2002). This backtracking phenomenon implies that group deformation may occur since the group members are evacuated in a rush and may be temporarily separated from one another; but they are very likely to regroup if dispersed. One more characteristic of group behaviors in evacuation is that pedestrians in the same group tend to pass through the same exit and keep their groups intact (Sime, 1995).

In order to model these characteristics, we assume that pedestrians in a group behave in accordance with the leader-follower rule. The existence of group leader in evacuation has been confirmed in many studies (see e.g., Fang et al., 2016). Based on the social psychology and behavioral theory, the leader in a group dominates the motion of the whole group and spatially holds an important position for easy communication (Moussaïd et al., 2010). Moreover, it is demonstrated that the leader-follower rule plays a key role on preserving the cohesion of pedestrian groups (Freud, 1975). In summary, the leader-follower rule is well grounded. With this in mind, we then set out to describe how to reflect the leader-follower rule in the proposed model.

This study assumes that the leader searches the path to the egress only based on the floor field, while the motions of group members depend on both the floor field and the leader. Therefore, the transition probabilities for the leader and other group members are formulated differently.

(a) To reflect the dependency of members on the leader, the parameter k'_s, $k'_s \in [0,1]$ is introduced as can be seen in Eq. (3) below. In order to represent the backtracking behavior of groups, it is assumed that the leader may stop with a probability of μ to wait for the other group members to return within a period of time. In this way, the separated members can attempt to find the leader.
(b) It is also considered that pedestrians in a group are likely to stay close to one another. This behavior is characterized by introducing the term $\exp(-k_d d_{lm})$, where d_{lm} is the distance between group members and leader, and k_d is a sensitivity parameter, which has a positive value. This term will lead the member to choose the cell closer the leader to move in.
(c) To capture the behavior that all the members in the same group tend to choose the same exit, we introduce the direction adjustment coefficient p_l, where the probability of choosing certain direction is proportional to p_l (see Eq. (3)). p_l is calculated as following: $p_l(i,j) = \exp(k_i)$ if a group member moves in the same direction as the leader, and $p_l(i,j) = 1$ for other cells. This formulation could force the group members to walk in the similar direction with the leader, thus finally leading to the same exit choice.

The aforementioned formulations enhance the cohesion of the group and make the group intact while evacuating. Based on the parameters introduced above, the transition probabilities for the group leader and other members are formulated as follows:

$$P_{i,j} = \begin{cases} N\exp(k_S S_{i,j})\exp(k_D D_{i,j})(1-\eta_{i,j})\varepsilon_{i,j} & \textit{for leader} \\ N\exp(k'_s S'_{i,j})\exp(-k_d d_{l,m})p_l(i,j)(1-\eta_{i,j})\varepsilon_{i,j} & \textit{for other members} \end{cases} \tag{3}$$

where $S'_{i,j} = k_S * S_{i,j}$; $d_{l,m}(i,j) = \sqrt{(i_l - i_m)^2 + (j_l - j_m)^2}$ is the distance between a group member's neighboring cell to the leader's position; (i_l, j_l) is the position of the leader, (i_m, j_m) is the position of the member's neighboring cell; $k'_s k_i$, k_d are the sensitivity parameters.

2.3. Procedures for model formulation and simulation

The room from which the pedestrians escape is discretized into cells that are either empty or occupied by one pedestrian at most at any time step. Each pedestrian can move to one of the unoccupied neighboring cells or stay at the current cell at each discrete time step with certain transition probabilities. The sequential update rule is adopted to renew pedestrian position, which means that at each time step, the pedestrian position is updated according to the order of the numbers randomly assigned to pedestrians.

The procedures for executing model formulation and simulating pedestrian movements are explicitly described as follows:

Step 1: Generate pedestrians and populate the pedestrians into the cells inside the room. Individuals and groups are generated in the target room with random positions. To identify whether a pedestrian is isolated or in a group, each pedestrian is given a unique ID. In addition, pedestrians in the same group are placed in adjacent cells in certain spatial structure. For pedestrians in group with size 2, they are placed in vertical or horizontal lines. Pedestrian groups of size 3 are in U-like, V-like or L-like shapes.

Step 2: Calculate the static floor field. The static floor field of each cell is determined by its distance to the exits, which remains unchanged during the simulation.

Step 3: Calculate transition probabilities and update positions. The transition probabilities of an isolated individual and a group leader are obtained based on the value of the floor fields. For other group members, the transition probabilities are calculated based on the leader's motion as well as the floor field. According to the transition probability, each pedestrian randomly chooses the target cell in the next time step.

Step 4: Update the dynamic floor field. The dynamic floor field is time dependent. Initially, the dynamic floor field is set to be zero for all cells. When the simulation starts, for each time step, the dynamic floor field of each origin cell where a pedestrian has moved out increases by one and decays with probability α, and diffuses to one of its neighboring cell with probability δ.

Step 5: For each pedestrian, repeat steps 3 and 4 until that pedestrian evacuates from the exit and is removed from the system.

3. Model calibration, simulation, and analysis

3.1. Model calibration

A few field experiments were performed to calibrate the associated parameters in the model. The experiments were conducted in a university building consisting of a hall and an adjacent passage leading to an emergency exit. Its geometry is shown in Fig. 2. Fifty-four participants were selected to participate in these experiments. The participants consisted of twenty-two isolated individuals, ten groups of size 2 and four groups of size 3. The participants are grouped based on their existing relationships. Under this configuration, the sizes of pedestrian groups obeyed a Poisson distribution (Moussaïd et al., 2010; Vizzari et al., 2013). At the starting time, all the participants were asked to stand in the university hall randomly. The participants in the same groups were requested to stay close to each other. They were instructed to evacuate from the hall to the emergency exit as fast as possible and behave in a natural manner as they would in a real emergency situation. Given a starting signal, they began to move towards the doors, entered the passage way and escaped from the exit.

The composition of individuals and groups in the aforementioned case is henceforth called Experiment A. In three other experiments with different group compositions, the same fifty-four participants were randomly divided into individuals, groups of size 2 and groups of size 3 with different numbers of groups in each of the three experiments, labeled as B, C, and D. The compositions of the four experiments A–D are shown in Table 1. Specifically, in Experiment B, the participants were asked to act as individuals and had no communication with others. The experiments C and D were carried out in the same manner, but in group sizes of 2 and 3, the participants were advised to consider the interest of their whole groups. The experiments repeated five times for each of the all four experiments.

It is worth mentioning that there are some inherent restrictions and limitations in this field experiment:

(a) Only in experiment A, the population was naturally divided into isolated individuals and groups according to their original relationships. In cases of C and D, the division of population into groups of size 2 and 3 was factitious since there are no specific social relationships among the assigned group members prior to the experiments;
(b) There was no real hazard presented for evacuation;
(c) Learning behaviors and residual effects from one experiment to the next may exist since the four cases were performed with the same population and each case was repeated five times.

For each case (i.e., A, B, C, D) of the four experiments, the evacuation time of each pedestrian was recorded. Due to the limited extent of image processing on recorded video, the detailed trajectories of each pedestrian evacuating are unavailable, so are the exact spatial distributions of pedestrian at each time step throughout the experiment. Thus, a method is introduced to estimate the walking speed of pedestrians, which is needed for later analysis. Note the average evacuation distance

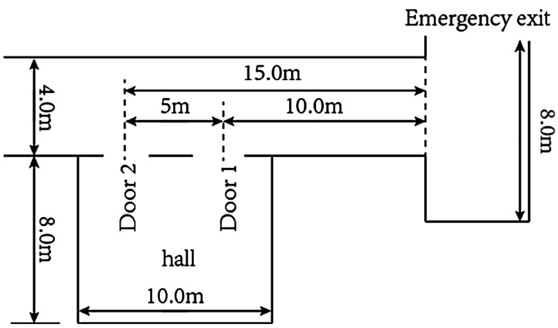


Fig. 2. The floor plan of a university hall.

Table 1
Results of evacuation experiment and simulation.

	Experiment				Simulation			
	A	B	C	D	A	B	C	D
Total numbers of pedestrians	54	54	54	54	54	54	54	54
Number of individuals	22	54	–	–	22	54	–	–
Number of groups of size 2	10	–	27	–	10	–	27	–
Number of groups of size 3	–	–	–	18	–	–	–	18
Number of runs	5	5	5	5	30	30	30	30
Mean walking speed (m/s)	1.52	1.57	1.46	1.44	–	–	–	–
SD of walking speed (m/s)	0.32	0.29	0.21	0.20	–	–	–	–
Mean evacuation time (s)	32.0	26.5	35.2	36.1	30.9	27.1	34.5	34.8
SD of evacuation time (s)	–	–	–	–	3.24	2.89	3.52	2.97

is calculated as the difference of distance between the center of the hall and the exit. Then for each student, the average speed is estimated as the ratio of the average evacuation distance to the time that the participant has taken to complete the evacuation process. The average speed of the participants in each experiment is subsequently used to determine the appropriate time step of simulation to match the time in field experiments. The mean value and standard variations of evacuation time and walking speed are analyzed and also presented in Table 1.

The computer simulations based on our proposed model are then conducted for each experiment, i.e., experiments A-D. For every composition, the simulations were run 30 times. The simulation results are summarized in Table 1 along with the field experimental results.

With the data at each time step captured from simulation data, we can graphically show the pedestrian movements during the evacuation process at different time instants. Fig. 3 illustrates the spatial distribution of pedestrians at two different time instants, t = 0 s and t = 20 s, respectively, in a simulation for experiment A. As can be seen, initially all pedestrians stayed at the room, after 20 s evacuation, all of them move to the pedestrian corridor. Fig. 4 compares the numbers of pedestrians evacuated through the emergency obtained from the simulations with the real-life experiments. It clearly shows that the simulation result well matches the real observation.

The procedures for calibrating the proposed floor field CA model with group behavior are explained as follows. We first performed several pre-test runs by varying values of the parameters and determined a rough threshold range of each parameter. Then, we varied the parameters from the lower bound to the higher bound within their respective ranges to compare the evacuation time obtained from simulation with that of field experiment. With this sequence of iterations, the trend of differences between the simulation results and the experimental results under monotonically variations of parameters can be analyzed. Then, a process is initiated to search for the optimal parameters, where the difference of evacuation time between field experiments and simulations was found to be minimal. As an outcome of this process, the best-fit parameters were determined to be: $k_s' = 0.6, k_d = 6, k_i = 5$. During the calibration process, μ was set to be 0.1 and other parameters were chosen in accordance with previous studies (Kirchner and Schadschneider, 2002). The results are presented in Table 1. Subsequently, *t*-tests were performed to compare the simulation and experiment results. It reveals that the difference of the evacuation time between the field experiments and simulations based on the calibrated model was not statistically significant. In other words, the simulated results from the model can represent the real life cases in a statistically significant manner.

3.2. Model validation

After model calibration, another case study is simulated to validate the movements of pedestrian groups and their impacts on evacuation dynamics by comparing the simulation results with the observed pedestrian dynamics from previous empirical studies. The simulations are performed with the configuration of a large room with size 20 m $*$ 20 m. There are two

(a) t=0s (b) t=20s.

Fig. 3. Illustration of pedestrian spatial distribution corresponding to Experiment A, t = 0 s and t = 20 s.

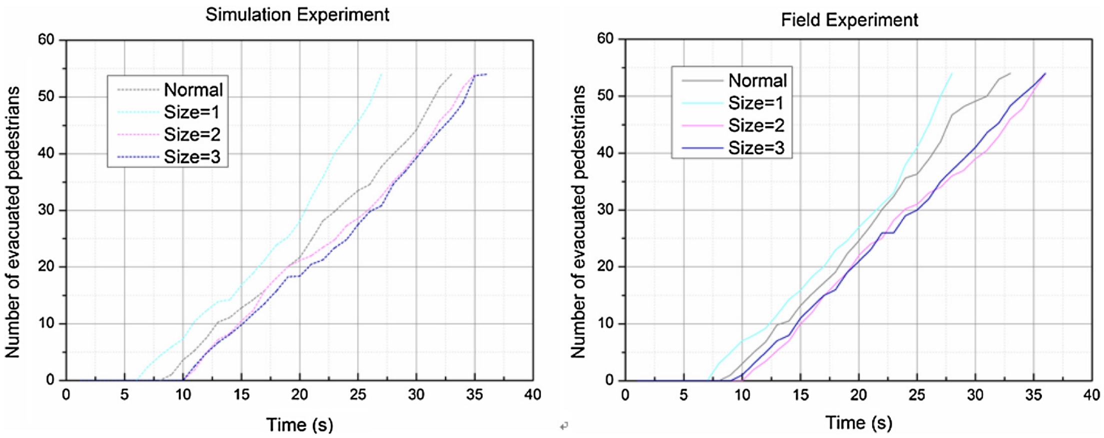


Fig. 4. Number of pedestrians evacuated through the emergency exit as a function of time.

doors with equal width of 2 m on the left wall, as depicted in Fig. 5. 750 pedestrians in total were generated to populate the room. We define density to be the quotient between the number of pedestrians and the total number of cells in the room. With 750 pedestrians, the density is calculated as 0.3. The 750 pedestrians are classified into groups with 60% of individuals, 26% of groups of size 2 and 14% of groups of size 3. Thus, the sizes of pedestrian groups followed the Poisson distribution, which was consistent with past studies (James, 1953; Moussaïd et al., 2010; Qiu and Hu, 2010). At the initial time, the isolated pedestrians were randomly distributed, while the pedestrian groups were distributed with certain spatial structure where members of the same groups stay together.

The variations of the dynamic floor field and distributions of the pedestrian crowd in the room at different time are shown in Figs. 6 and 7, respectively. Fig. 6 depicts the dynamic field with a 3-D representation in the hall. In Fig. 7, pedestrian groups of different sizes are identified by circles of different colors to illustrate the process of moving toward and evacuating from the exits. The black empty circles in Fig. 7 represent isolated individuals, and the red and green ones represent members of pedestrian groups of sizes 2 and 3, respectively.

It is observed that during the evacuation process, the arch-like collective blocking around the two exits occurs at t = 20 s when the crowd aggregately reaches the doors. The total evacuation time is about 150 s for this case, considerably longer than the time for the crowd to initially getting close to the door. This is due to the fact that pedestrians spent a lot of time aggregating near the exits to find a way out, resulting in a relatively high value of dynamics floor field around the doors. These patterns reproduced by our simulation model turn out to be consistent with empirical observations in a previous study (Helbing et al., 2001).

3.3. Impacts of pedestrian groups on evacuation dynamics

To further investigate the group movements, we also track some groups of size 2 to observe their spatial structure during the evacuation process (see Fig. 7). By observing the graphic image sequences generated from the simulation, it is found that

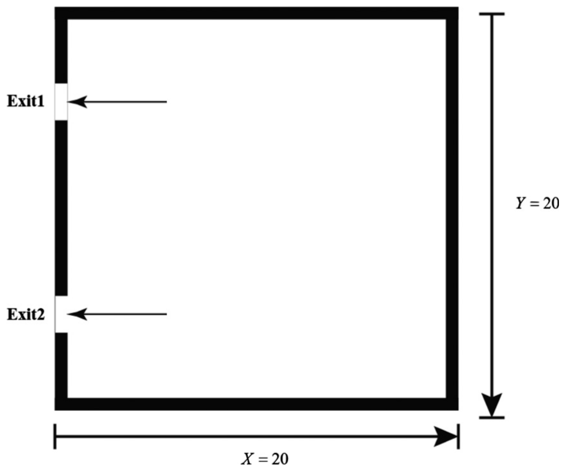


Fig. 5. Schematic illustration of the spatial configuration for a case study.

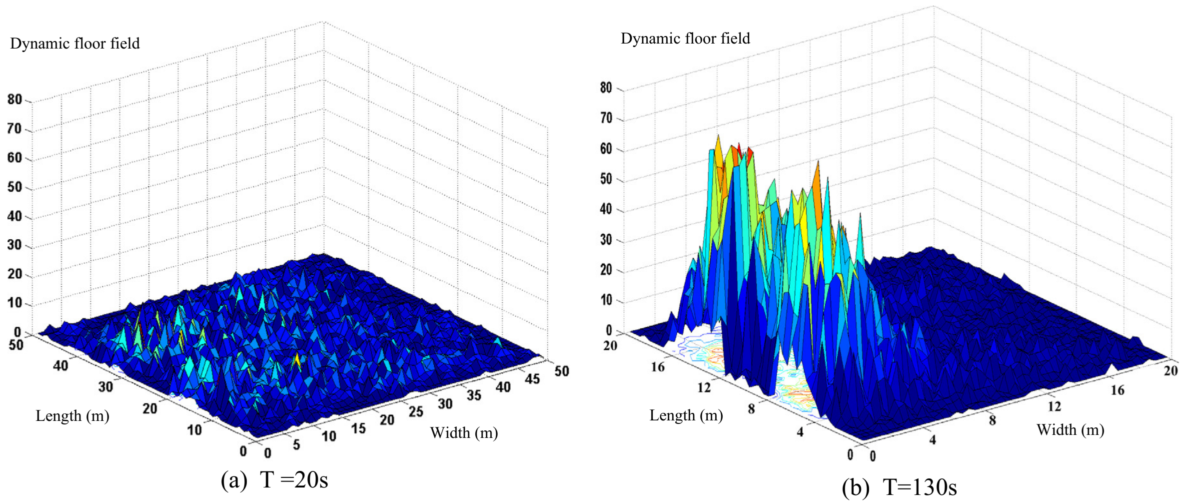


Fig. 6. Dynamics floor field at different times in simulation.

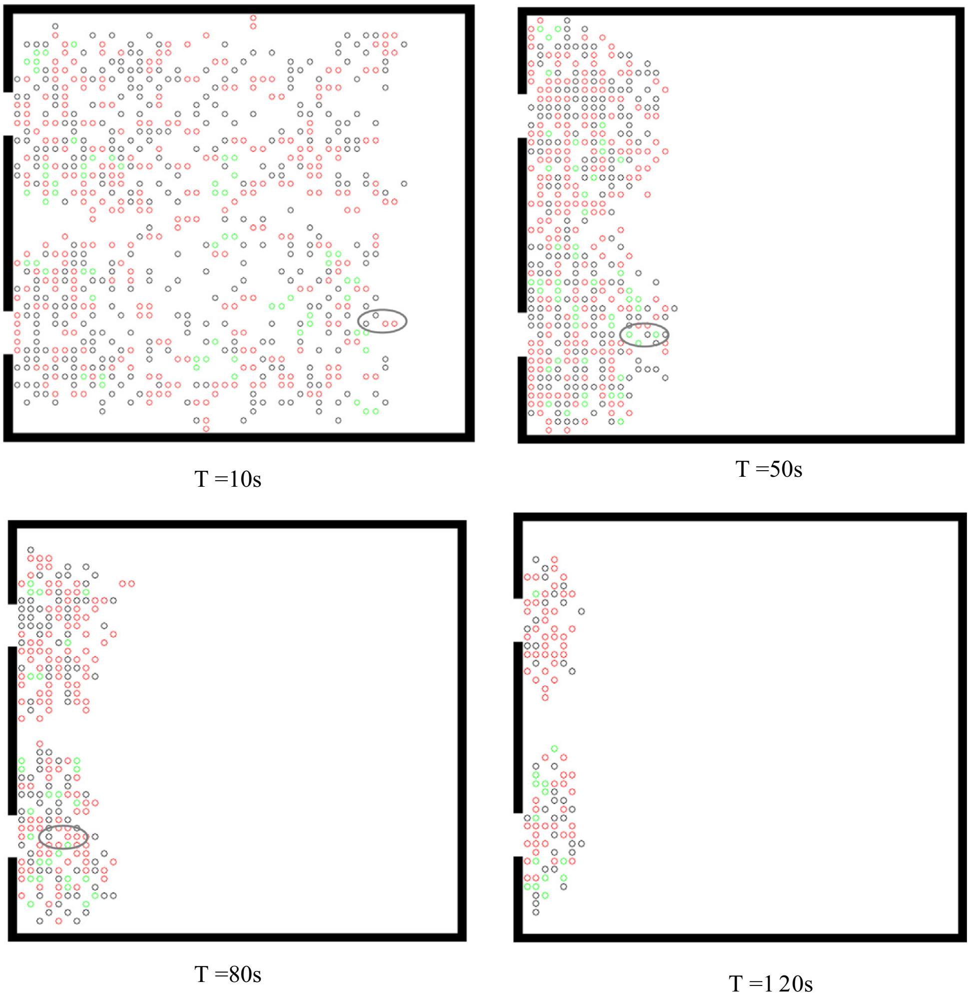


Fig. 7. Simulation results at different times: 0 s, 50 s, 80 s, 120 s.

for most of the time, the members in groups of size 2 were capable of maintaining their adjacency and walking side by side or in a line. Only in rare cases, their structures are temporarily broke up in order to circumvent the other people on their paths. However, the groups of size 3 were found to be easily split and frequently lost one of their members. This is reasonable as it can be expected that the larger the size of groups is, the harder it will be for all the group members to stay together. For comparison, we conducted two more simulation experiments with only 60 pedestrians, as opposed to 750 in the case above. Thereby, we have much lower initial density compared with the first case of 750 pedestrians discussed above. The 60 pedestrians were divided into groups of sizes 2 only in the first simulation and groups of sizes 3 only in the second simulation experiments. It was observed that both groups of sizes 2 and size 3 had specific spatial structures that stayed relatively unchanged. The average distances among the pedestrians in the group were calculated from the simulation model by incorporating the calculation into the model algorithm. In the case of 750 pedestrians, the average distance between the members in the groups of size 2 is 0.85 m during the evacuation, while it is 0.91 m in the groups of size 3. In the two simulation experiments with 60 pedestrians in groups of size 2 and 3 only, the average distances between the pedestrians in the group of size 2 and group of size 3 are 0.76 m and 0.80 m, respectively. This finding implies that the spatial structure of group may be broken in a dense crowd but it can manage to stay stable in lower density cases. Further, the choices of exits of each member in groups are examined with the simulation results. It is found that for 90.3% of the total groups, the members in the same group would choose the same exit in the case with 750 pedestrians while the percentage increases to 100% when there are only 60 pedestrians to evacuate.

Based on the validated model, we then evaluate the impacts of pedestrian groups on total evacuation time, which is the most important indicator of crowd evacuation in practice. The simulation uses a hall with the same spatial configuration as it is shown in Fig. 5. First, we compare the total evacuation times of the case with 750 people divided in different group sizes. The following cases are tested, each of which only comprise one certain type of pedestrians: (1) isolated pedestrians only, (2) groups of size 2 only, or (3) groups of size 3 only, respectively. For each of the three different group compositions, the simulations were run 30 times, and the total evacuation time and the number of people remained in the room at each time step were obtained and averaged. Fig. 8 presents the mean number of pedestrians remaining in the room at each time step for different group sizes. They are averaged across the 30 simulation runs. It can be seen that when the population are all isolated individuals (group size = 1), the average total evacuation time is approximately 125.3 s. For the cases in groups of sizes 2 and size 3, the average total evacuation time are 150.6 s and 157.2 s, respectively. The mean values and standard deviations are listed in Table 2. *t*-Tests were conducted to check whether the differences in evacuation time for pedestrian groups with different sizes were statistically significant. The result shows that the differences of evacuation time are statistically significant between the crowd of individuals and the crowd consisted of groups with size 2 only (p-value < 0.01), as well as the crowd with groups of size 3 only (p-value < 0.001). However, the difference of evacuation time between groups of size 2 and size 3 is not statistically significant (p-value = 0.141).

Fig. 8 also demonstrates that at each time step, the downward slope of the green dashed line (represents the cases with individuals only i.e., no groups) is steeper than that of the two other lines (represents the cases with groups of size 2 or size 3) most of time along the evacuation process. This indicates that if the crowd consists of individuals only, a greater number of people would be evacuated at each time step in the evacuation process than that with groups. The pink and blue lines for groups of size 2 and size 3 share a similar trend and their total evacuation times are approximately the same. From the analyses above, it is evident that pedestrian groups have significant impacts on evacuation dynamics, and a larger number of pedestrians would be delayed if they are evacuated in groups. This is probably so because when pedestrians evacuate in groups, their moving velocity and moving direction are affected by the other members in the group. The pedestrians in a group with fast moving velocity will wait for the slower ones since they tend to sustain a spatial arrangement, which increases the evacuation time. In addition, the behavior of backtracking may also contribute to the increased evacuation

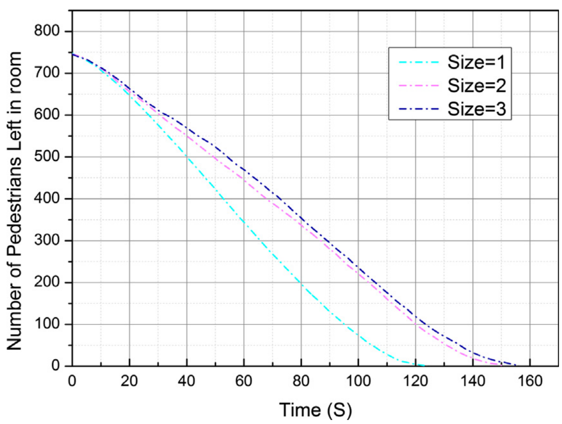


Fig. 8. Number of pedestrians left in the room at each time step for different group sizes.

Table 2
Results of t-tests for evacuation time.

	N	Mean(s)	SD	p-Value	
Group Size=1	30	125.3	8.41	<0.01 (Size 1 vs 2)	<.001 (Size 1 vs 3)
Group Size=2	30	150.6	12.26	0.141 (Size 2 vs 3)	
Group Size=3	30	157.2	15.81		

time. Moreover, the groups with certain spatial structure will interfere with the movement of other pedestrians. This is particularly obvious when the crowd is clogging the egress. However, the negative effects of groups do not increase proportionally with the increased group size as revealed by the comparison of group sizes of 2 and 3.

The evacuation dynamics are further assessed with different crowd densities. Fig. 9 shows the evacuation time under different density levels and group sizes. Two observations can be obtained from Fig. 9. First, like the insignificant differences between groups of size 2 and size 3 in the previous section, the difference in evacuation time between group of size 2 and size 3 is very similar as the density changes, showing no major differences between them. But the evacuation time of both groups of size 2 and size 3 is saliently different from that of a crowd consisting of individuals only. This pattern occurs because the members in a pedestrian group are more likely to be separated from one another at higher density. As a result, the frequencies of backtracking behaviors of group members and waiting behaviors of the group leaders increase during evacuation. All the results presented here are obtained with the same calibrated model that possesses the best-fit parameters described in the previous section.

3.4. Parameter sensitivity analysis

In our model, the behaviors of pedestrian groups are mainly controlled by three sensitivity parameters, k_s', k_d and k_i. The mechanism underlying the prementioned group behaviors can be revealed by conducting sensitivity analyses of these parameters. The impacts of each parameter on evacuation time resulting from sensitivity analyses are further described as follows. As denoted before, k_s' is the sensitivity parameter representing the strength of dependency on the static floor field when group members make decisions for evacuation. To observe the sensitivity of the evacuation time with respect to k_s', k_d and k_i are fixed at the best-fit values, i.e., 6 and 5 respectively. The trajectory of corresponding evacuation time as k_s' changes from 0 to 1 is obtained with the simulation model, and results of which are shown in Fig. 10(a). It indicates that when $k_s' = 0$, the total evacuation time is at the maximum value; however, when $k_s' = 0.1$, the evacuation time decrease dramatically to 168 s, and as k_s' increases from 0.1 to 1, the evacuation time experiences a moderate decrease from 168 s to 155 s. When $k_s' = 0$, the movements of group members will completely depend on the group leader and have nothing to do with static floor filed. Recall at $k_s' = 1$, the movements of group members are dependent, with equal weightings, on both the static floor

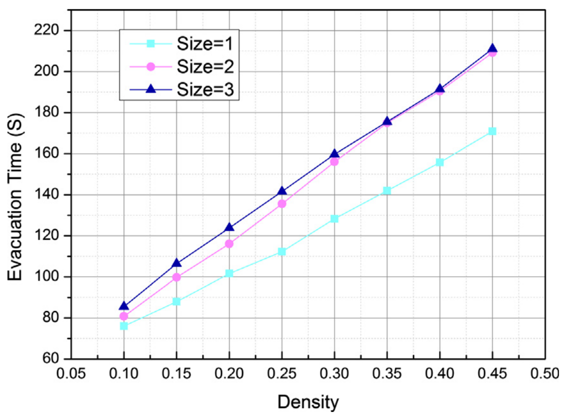
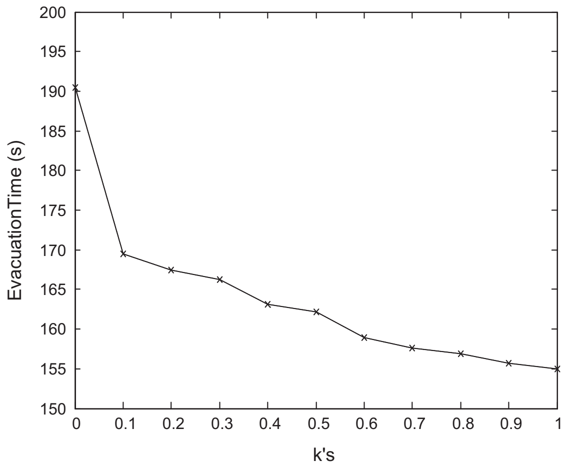
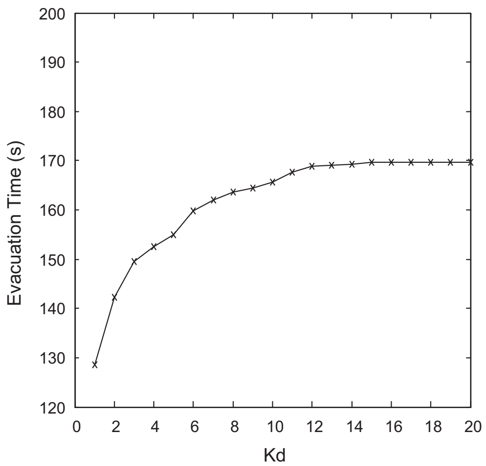


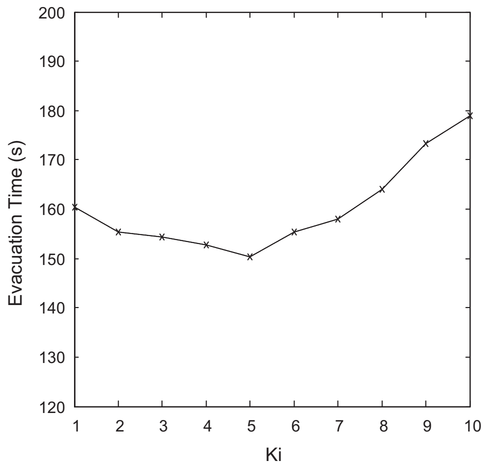
Fig. 9. Evacuation time under various density levels for different group sizes.



(a) Evacuation time as a function of $k'_s, k_d = 6, k_i = 5$



(b) Evacuation time as a function of k_d, $k'_s = 0.6, k_i = 5$



(c) Evacuation time as a function of k_i, $k'_s = 0.6, k_d = 6$

Fig. 10. Evacuation time as a function of different sensitivity parameters.

field and the motion of the group leader. Thereby, Fig. 10(a) implies that as k'_s increases, pedestrians in a group will totally rely on the motion of the leader and abstain seeking the shortest path by themselves to the exit, leading to inefficient evacuation.

The parameter k_d reflects the strength of the group member's desire to stay close to the leader. The effects of k_d is shown in Fig. 10(b). These results are obtained by fixing k'_s and k_i at the optimal values 0.6 and 5, respectively. When k_d is 1, the group member behaves more like an isolated individual and the group is unable to maintain stability. Besides, it seems that external factors such as the presence of other people or obstacles have no influence on the behavior of groups, which contradicts the basic definition of a group. Therefore, k_d is very critical for pedestrian group behavior modeling and should be set properly to offer sufficient cohesion for group formation. A higher value of k_d, however, will result in increased evacuation time as depicted in Fig. 10(b). It can be interpreted that when k_d becomes larger, the pedestrians in the group are more likely to move together, which, in all aspects, will reduce the evacuation efficiency.

The curve in Fig. 10(c) shows the change of total evacuation time as k_i increases. These results are obtained by fixing k'_s and k_d at the optimal values 0.6 and 6, respectively. As clearly illustrated in the figure, the effects of parameter k_i on evacuation time is not monotonic throughout the range of its variation. When k_i is less than 5, the total evacuation time decreases gradually with respect to increased k_i. This may be due to the fact that when k_i is set within this range, the members in a group would wander around the leader during evacuation, indicating that they are not able to reach a consensus on the direction of movement, and behave more like an individual. In this case, a slight increase of k_i will result in a moderate decrease in evacuation time. Nevertheless, when the value of k_i exceeds 5, the trend reverses. That is, the evacuation time increases with a rise in k_i. The interpretation of this effect is similar to that of k_d, i.e., if the group members totally trust the leader and always move in the same direction as the leader, the evacuation time may be significantly extended.

4. Conclusions

This paper presents an extended CA simulation model that incorporates the pedestrian group behaviors in crowd evacuation situations. By incorporating the leader-follower rule in the group behaviors, we are able to establish and validate an extended CA model that well captures the characteristics of group movements during the evacuation process and successfully predicts total evacuation time.

A few field experiments of pedestrian evacuation are conducted in a university building to calibrate the proposed extended CA model. Computer-based simulations are then performed by leveraging the calibrated extended CA model. The results validate that the fundamental phenomenon of arch-like clogging with the crowd collectively aggregating at the exit can be well reproduced by this model. In particular, we observe that, the total evacuation time increases with the presence of pedestrian groups in the crowd. This effect is amplified when the crowd density is higher. In addition, group behaviors are investigated by conducting sensitivity analyses of model parameters to show their impact in the evacuation process.

With the proposed model capable of replicating the pedestrian evacuation in field experiment, insights gained in our study can be very valuable for evacuation planning. For example, it can be used for optimizing the layout of exits in buildings and guiding pedestrians for emergency evacuation, in particular when a significant portion of the crowd acts in groups. We do recognize a shortcoming in the field observation experiments, in which the individual pedestrian trajectories are not fully captured. This hinders a more in-depth analysis of individual pedestrian trajectories in field experiments and a detailed comparison with those step-by-step data obtained from simulations. We envision that this limitation can be overcome in future studies by an improvement with more elaborate video recording and image processing techniques. We also expect that collecting more field data from different evacuation scenarios will enhance the understanding of group behaviors. The performance of the proposed model can be further validated under various conditions and building configurations, which will ultimately provide us with a powerful tool for academic endeavors as well as for real-world crowd management practices.

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