

Static floor field and exit choice for pedestrian evacuation in rooms with internal obstacles and multiple exits

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A modified floor field model is proposed to simulate pedestrian evacuation in rooms with internal obstacles and multiple exits. The modifications lie in developing a method to calculate the static floor field for every lattice site, which is determined by the most feasible distance to an exit, and employing a logit-based discrete choice principle to govern the exit selection. Simulation results show that the evacuation time is sensitive to the exit position and some model parameters. For pedestrians unfamiliar with the exit location, additional doors may not be necessary and can cause a negative effect on evacuation time. It is also found that unfamiliarity with the room's inner configuration and blindly following others will lead to an increase of the evacuation time.

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I. INTRODUCTION

Pedestrian modeling is one of the most exciting fields in traffic science and engineering [1–28]. The reason is that understanding pedestrian flow characteristics beforehand is very important in designing or improving such public places as waiting rooms in railway or bus stations, supermarkets, banquet halls, meeting rooms, theaters, and movie houses. The dynamic properties of pedestrian crowds, including various self-organization phenomena, have been observed and successfully reproduced by various physical methods. However, pedestrian evacuation is much more difficult to observe than normal pedestrian flow because of the danger and panic caused by incidents. A real-life experiment for evacuation is almost impossible. This encourages researchers to study evacuation behavior by various modeling approaches [2,3,6,8,12–19,26–28].

Pedestrian flow has been studied by simulation models [1–19,26–28] and empirical or experimental investigations with video analyses [5,19–25]. These models can be classified into two categories, continuous [1–5] and discrete [6–19]. The continuous models can be reduced to a differential equation system describing the relations among speed, density, and flow. The discrete models are mainly the lattice gas [6–9,19,28] and cellular automata (CA) models [10–18]. The floor field (FF) model [14–18] is one class of CA model. It finds favor in researchers' eyes because many characteristic aspects of the pedestrian dynamics can be reproduced by this model, particularly the different collective effects which are observed empirically but cannot be explored by other CA models.

To our knowledge, some research of simulating pedestrian evacuation in rooms with internal obstacles [14,19] or multiple exits [16,29] has been conducted, but little research has considered evacuation in rooms with both internal obstacles and multiple exits, though this scenario indeed exists in the real world. In this paper, we improve the FF model for simulating pedestrian evacuation in rooms with both multiple ex-

its and interior obstacles. A method for computing all lattices' static floor field values is proposed and the logit-based discrete choice principle is incorporated in the model to formulate the exit choice behavior. Three scenarios where people in danger try to escape from a room with the same internal obstacles but different exit positions are simulated. The impacts of exit position and some model parameters on the evacuation time are investigated.

II. MODEL

In the proposed model, the space is represented by two-dimensional square lattices. The size of each lattice site is approximately $40 \times 40 \text{ cm}^2$. Each site can be either empty or occupied by exactly one pedestrian. Pedestrians are randomly distributed in the room at the initial time of simulation. In each time step, pedestrians move only one lattice site in the forward, backward, left, or right directions or remain unmoved.

Figure 1 shows possible transitions and corresponding transition probabilities for a pedestrian at each time step. In the figure the lattice position is denoted by its relative position, and the physical position can then be defined. In the following the position of each lattice site refers to its physical position. The transition probability $P_{i,j}^m$ that a pedestrian intends to leave the room from door m represents the possibility of selecting the neighboring lattice (i,j) . As in [16], this probability is determined by the local dynamics and the floor fields corresponding to exit m at that lattice site, i.e.,

$$P_{i,j}^m = N \exp(k_S S_{i,j}^m) \exp(k_D D_{i,j}^m) (1 - \mu_{i,j}) \xi_{i,j}, \quad (1)$$

where N is a normalization factor to ensure that $\sum_{(i,j)} P_{i,j}^m = 1$. $S_{i,j}^m$ and $D_{i,j}^m$ in Eq. (1) are the values of the static and dynamic floor fields corresponding to exit m at lattice site (i,j) , respectively. The static field $S_{i,j}^m$, which is initialized at the beginning of the model run, is a gradient having high values near desirable areas (e.g., exits) and low values elsewhere. The dynamic field $D_{i,j}^m$ is the number of bosons corresponding to exit m at lattice site (i,j) . Here, the bosons depict the virtual traces left by moving pedestrians and their dynamics proceed through diffusion and decay. The bosons are

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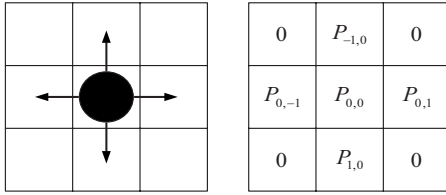


FIG. 1. Possible transitions and corresponding transition probabilities.

dropped by moving pedestrians who intend to leave the room through exit m . Initially, lattices contain no bosons. When a pedestrian moves from the lattice (i, j) to a neighboring lattice, he or she drops a boson at the departure lattice. Suppose that each boson decays with a probability δ in each time step and some bosons without decaying diffuse (randomly move to a neighboring lattice) with the probability α . For one lattice, there may exist different static and dynamic field values which correspond to different exits. The reason for using this regulation will be illustrated in the following section. In Eq. (1), k_S and k_D are two sensitivity parameters for scaling $S_{i,j}^m$ and $D_{i,j}^m$, respectively. The value of k_S can be regarded as a measure of the pedestrians' knowledge about the inner configuration of a room. The parameter k_D reflects the tendency that a pedestrian follows the leader of others in the process of evacuation. In Eq. (1), $\mu_{i,j}$ indicates whether the neighboring lattice (i, j) is occupied. It is 1 if the lattice is occupied and 0 otherwise. $\xi_{i,j}$ is related to the existence of obstacles. It is 0 if the neighboring lattice site (i, j) cannot be used due to some obstacle (e.g., walls, racks, or shelves) and 1 otherwise.

Therefore, the basic dynamics of a pedestrian, as described by Eq. (1), is in fact characterized by (i) a static floor field, which should be taken so that the motion toward an exit is preferred, and (ii) a dynamic field, which measures the interaction among the individuals. In this paper, we propose a method to calculate the static floor field values of all lattices.

A method for calculating the static floor field values in rooms without internal obstacles was proposed in [16]. This method cannot work in rooms with many obstacles. In this study, we develop a method to solve this problem. We first introduce the parameter $d_{i,j}^m$, which represent the most feasible distance from lattice site (i, j) to exit m . It is computed in the following steps.

Step 1. For each lattice site (i, j) in a room (excluding the door lattices outside the wall), let $f_{i,j}^m=0$ and $e_{i,j}^m=0$ if the lattice site (i, j) is not occupied by obstacle, and $f_{i,j}^m=-1$ and $e_{i,j}^m=-1$ otherwise. Set $k=1$.

Step 2.1. Check neighboring lattice sites (i, j) in forward, backward, left, and right directions of the door lattices, and let $f_{i,j}^m=k$ for those lattice sites with $f_{i,j}^m=0$.

Step 2.2. For each lattice site inside the room (i_0, j_0) with $f_{i_0,j_0}^m=k$, check its neighboring lattice sites (i, j) in forward, backward, left, and right directions, and let $f_{i,j}^m=k+1$ for those neighboring lattices with $f_{i,j}^m=0$.

Step 2.3. If $f_{i,j}^m \neq 0$ holds for all lattice sites inside the room, then $k \leftarrow 1$ and go to step 3.1; otherwise, $k \leftarrow k+1$ and go to step 2.2.

Step 3.1. Check the neighboring lattice sites (i, j) in the

forward, backward, left, and right directions of the door sites; let $e_{i,j}^m=k$ for those lattices with $e_{i,j}^m=0$.

Step 3.2. For each lattice site inside the room (i_0, j_0) with $e_{i_0,j_0}^m=k$, check all its neighboring sites (i, j) (include the lattice sites in the diagonal directions); let $e_{i,j}^m=k+1$ for those neighboring lattice sites with $e_{i,j}^m=0$.

Step 3.3. If $e_{i,j}^m \neq 0$ hold for all lattice sites inside the room, go to step 4; otherwise, $k \leftarrow k+1$ and go to step 3.2.

Step 4. For each lattice site (i, j) , compute $d_{i,j}^m = \varepsilon f_{i,j}^m + (1 - \varepsilon)e_{i,j}^m$, where $0 \leq \varepsilon \leq 1$.

In the above steps, $f_{i,j}^m$ is the minimal number of lattice sites experienced by a pedestrian in lattice site (i, j) who leaves the room through exit m , when only movement in the horizontal or vertical direction is permitted, and $e_{i,j}^m$ is the minimal number of lattices when movements in all eight directions are permitted. The most feasible distance to exit m is the weighted sum of $f_{i,j}^m$ and $e_{i,j}^m$. In fact, the ε value has influence on the shape of the crowd near an exit, as illustrated in Sec. III by numerical simulation. The ε value should be set to keep the shape of the crowd near the exit be in accordance with the observed one.

The most feasible distance calculated by the above process is similar to that obtained by the process proposed in [14]. However, there are essential differences between them in the implementation and fundamentals. In the above process, the distances of all neighboring lattice sites around a lattice site are updated according to the most feasible distances of that lattice site to exits. In [14], in contrast, the floor field value of a lattice site is obtained according to the floor field values of its neighboring lattice sites. Applying the process of [14] to a room with $n \times (2n+2)$ internal lattice sites and two door lattice sites located at the middle of a long wall (i.e., a wall of $2n+2$ lattice sites), the floor field values of $2n^2-6n+6$ and $6n-8$ lattice sites have to be computed through by three neighboring and two lattice sites, respectively. These computations are not required in the process proposed in this study.

The static field value of site (i, j) in Eq. (1) is then given by

$$S_{i,j}^m = d - d_{i,j}^m, \tag{2}$$

where $d = \max_m \{ \max_{(i,j)} d_{i,j}^m \}$. In summary, the method proposed in this study gives the static field values using the principle that pedestrians intend to move to a neighboring site that is closest to the exit in the most feasible direction.

Figure 2 presents the most feasible distances from lattice sites to the exit, considering the evacuation process of four pedestrians (denoted by shaded circles) in a room with two internal obstacles (denoted by shaded rectangles). Figure 2(a) is subject to $\varepsilon=1$, Fig. 2(b) to $\varepsilon=0$, and Fig. 2(c) to 0.5. The distance is given by the number in each lattice site. It can be seen that pedestrians behind obstacles can select reasonable neighboring lattice sites for their next time step's movements.

In a room with internal obstacles and multiple exits, it is generally difficult for a pedestrian to find an optimal exit for his/her evacuation within a short time. This is particularly true in the case of urgency. Some researches employed the

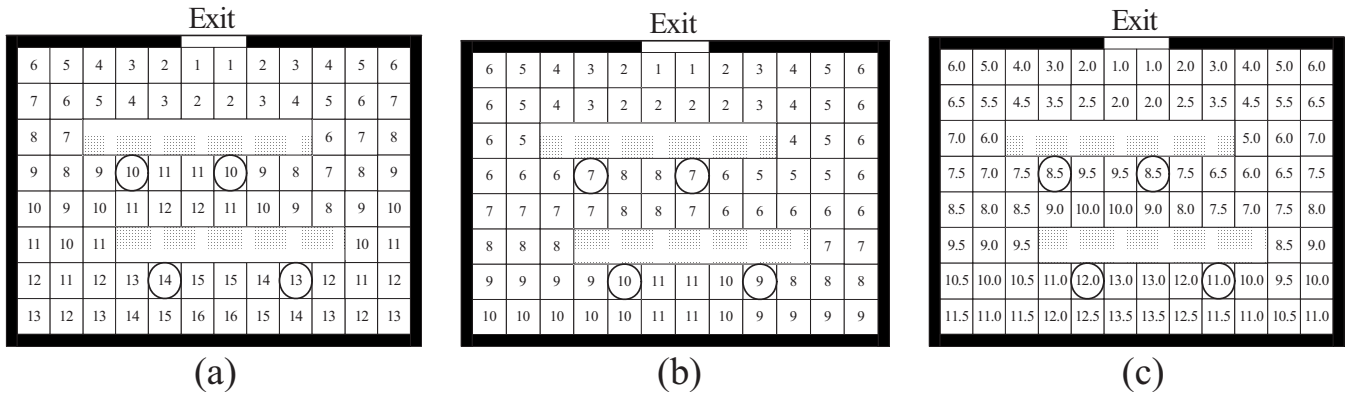


FIG. 2. Most feasible distances from lattices to the exit when ε takes different values, ε =(a) 1, (b) 0, and (c) 0.5. There are four pedestrians (denoted by circles) in a room with two obstacles (denoted by shaded rectangles) and an exit. The room is discretized into an 8×12 lattice.

software SIMULEX [29] to simulate pedestrian evacuation in rooms with multiple exits, but how to formulate the exit choice behavior is still an open problem. In this paper, we apply the logit-based discrete choice principle to formulate the exit choice behavior with consideration of the uncertainty of finding the exit. Suppose that the uncertainty is mainly caused by the variation in perceiving the static floor field. The probability of selecting exit m for a pedestrian who is occupying site (i, j) is given by [30]

$$Q_{i,j}^m = \frac{\exp(\theta S_{i,j}^m)}{\sum_l \exp(\theta S_{i,j}^l)}, \quad (3)$$

where θ (≥ 0) is a parameter related to the perception variations and l the index for a general exit. A larger θ means a smaller perception variation of the static floor field. Hence, the parameter θ can be used to reflect the degree of familiarity of pedestrians with the exit location information. Some pedestrians are unfamiliar with the exit location information and thus leave the room not by the closest exit.

Finally, we give an overall outline of the model run as follows.

Step 1. Calculate $d_{i,j}^m$ for all sites using the process proposed in this paper. Compute the static field value $S_{i,j}^m$ for all lattice site to exit pairs by Eq. (2).

Step 2. Let each evacuee probabilistically select an exit, using Eq. (3).

Step 3. Let each pedestrian probabilistically select a direction for movement, using Eq. (1), and move one site in the direction (or remain unmoved).

Step 4. Stop if the number of pedestrians in the room is zero; go to step 3 otherwise.

III. SIMULATION RESULTS

First, we examine the influence of the ε value in the most feasible distance formula on the shapes of crowds near exits. In this simulation, suppose that 1200 randomly distributed pedestrians attempt to escape from a room having an 80×100 lattice. The time step is 0.3 s, which implies a walking speed of approximately 1.33 m/s. There is no obstacle in the room. Four exits, each three sites wide, are located at the

centers of the four walls. It is assumed that almost all pedestrians leave the room by the closest exit ($\theta=1$). Let the parameters k_S, k_D, δ , and α be 5, 0.5, 0.5, and 0.5, respectively. Figures 3(a)–3(f) display the typical stages of the pedestrians' evacuation at time step 40 when ε takes six different values. It can be seen that when $\varepsilon=0$ the vertical and horizontal sizes of the crowd are relatively small and the diagonal size is relatively large. With an increase of the ε value, the vertical and horizontal sizes of the crowd increase, but the diagonal size decreases. When $\varepsilon=0.4$, the shape of the crowd is approximately a semicircle. An unreasonable shape occurs when $\varepsilon=1$. From the simulation, the ε value should be within the range [0.4, 0.6]. It should be stated that, in addition to ε , the parameters k_S, k_D, δ , and α also have influence on the shape of the crowd. We found that, for specific combinations of these parameters, ε should be set within a specific range to keep the shape of the crowd approximately semicircular, a commonly observed scene.

Now suppose that 500 randomly distributed pedestrians attempt to escape from a room with an 80×100 lattice and 22 inner obstacles. To investigate the effects of door number and position on evacuation time, we consider three scenarios shown in Fig. 4. In these three scenarios, the door number and position are different from each other, but the total width of all doors is 12 lattice sites for each. The time step is 0.3 s. The decay probability is $\delta=0.5$ and the diffusion probability $\alpha=0.5$. Our study is focused on the influences of the parameters θ, k_S , and k_D on the pedestrian evacuation time, as other parameters remain unchanged. We conducted 20 simulations for each set of parameters and record the mean value and variance of the average evacuation time. The average evacuation time reported below is the average of all pedestrians' evacuation times.

Figures 5 and 6 depict the mean values and variances of evacuation times against different θ values, each with a specific set of k_S and k_D . In these figures, M_1, M_2 , and M_3 are the mean values of evacuation times obtained in the three scenarios defined in Fig. 4, respectively. V_1, V_2 , and V_3 are the corresponding variances of the evacuation times.

Figure 5 shows that in each scenario the mean value of the evacuation time decreases nonlinearly with increasing θ value. This is certainly reasonable because a larger θ value

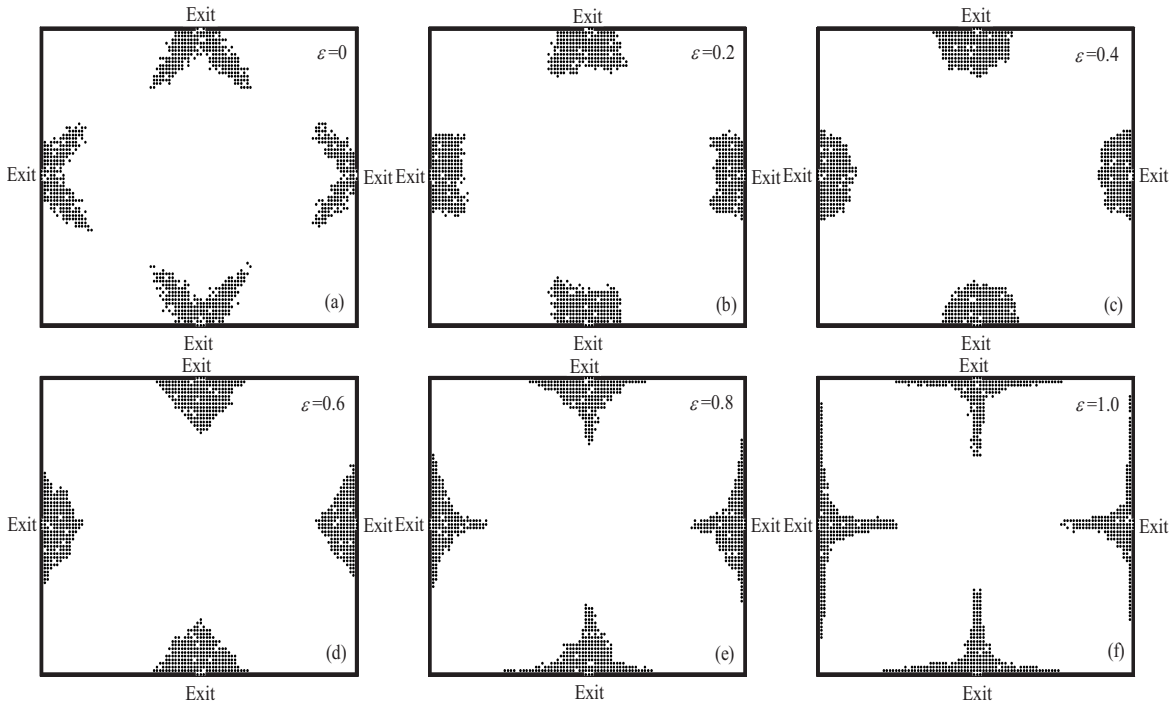


FIG. 3. Typical stages of the pedestrians’ evacuation at time step 40 when ε takes different values. ε =(a) 0, (b) 0.2, (c) 0.4, (d) 0.6, (e) 0.8, (f) and 1.0.

means a higher degree of familiarity of pedestrians with the door location information. With increase of the θ value, they tend to leave the room from the closest exit. When the θ value exceeds 1, almost all pedestrians leave the room through the closest exit, and their evacuation time stays unchanged. Comparing the three curves describing the mean values, we find that for all θ values the mean values of the evacuation times in scenario 1 are always smaller than those in the other two scenarios. Thus, arranging four exits at the centers of four walls is the best solution. It is interesting that when the θ value is less than $10^{-1.5}$, scenario 3 with two exits is better than scenario 2 with three exits. However, when the θ value exceeds $10^{-1.5}$, which implies pedestrians know the door location information well, scenario 2 becomes better than scenario 3. Thus, for pedestrians unfamiliar with the exit location, additional doors are not necessary and can cause a negative effect on evacuation time due to the inefficient interaction among pedestrians. In addition, it can be seen from Fig. 5 that, compared with the mean value of evacuation time, the variance is very small. This provides support for evaluating different scenarios through comparing the mean values of evacuation times.

Figure 5 also shows that, when k_D varies from 0 to 1, the mean value of evacuation time almost stays unchanged for each scenario. When k_D increases from 1 to 3, the mean value of evacuation time obviously increases. This shows that, whether or not a room has internal obstacles and pedestrians are familiar with the exit location, more blindly following others (i.e., a relatively high k_D value) will cause increase of the evacuation time.

In Fig. 6, k_D is kept at 0.3 but k_S varies from 1 to 4. It can be seen that for each scenario the mean value of evacuation time decreases with increasing k_S . This is understandable because k_S is a measure of the individual’s knowledge about the room’s inner configuration. A larger k_S means that pedestrians leave the room with few detours, and a small k_S implies they have little knowledge about the room configuration. Even if they know the position of a certain exit, they may make a detour and spend more time reaching the exit. This shows that, whether or not a room has internal obstacles and pedestrians are familiar with the exit location, their unfamiliarity with the room’s inner configuration (i.e., relatively small k_S value) may lead to a longer evacuation time.

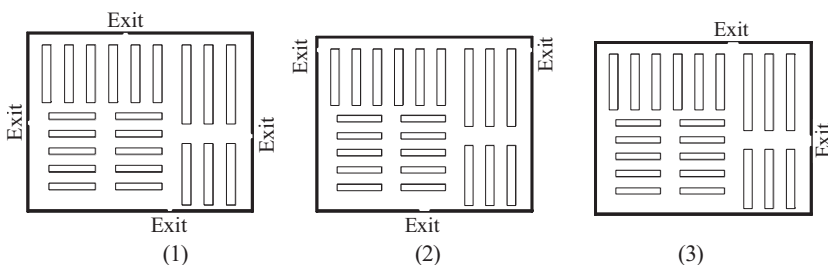


FIG. 4. Three simulation scenarios with the same internal obstacles (denoted by small rectangles) but different exit positions. The total width of the exits is identical for these three scenarios.

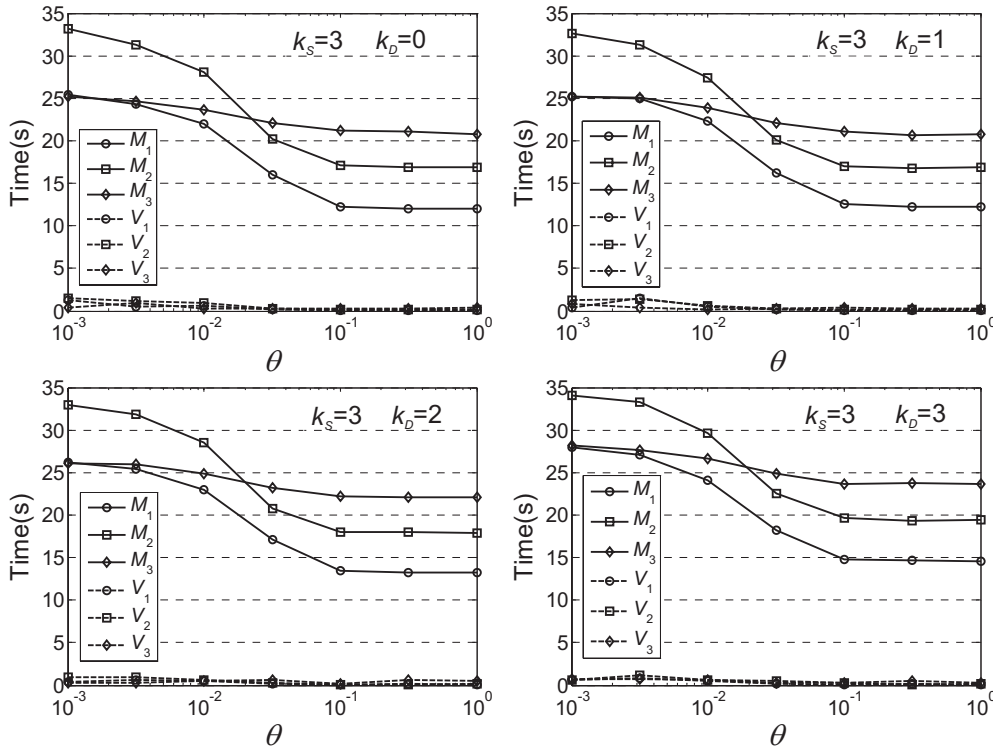


FIG. 5. Mean values and variances of evacuation times against θ when k_S is kept at 3 and k_D takes four different values 0, 1, 2, and 3.

IV. SUMMARY

To sum up, a modified floor field model is proposed in this paper to simulate pedestrian evacuation in rooms with internal obstacles and multiple exits. The modifications lie in the process of calculating the static floor field for each lattice site which is determined by the most feasible distance from the lattice to an exit. This most feasible distance is set to be

the weighted sum of two distances. One comes from the case of permitting only vertical and horizontal movements, and the other from permitting movements in all eight directions. It is found that only when the weight coefficient is taken in a certain range, is the shape of the crowd near each exit a semicircle. In addition, the logit-based discrete choice principle is incorporated in the model to govern the exit selection behavior of pedestrians and reflect the uncertainty in finding

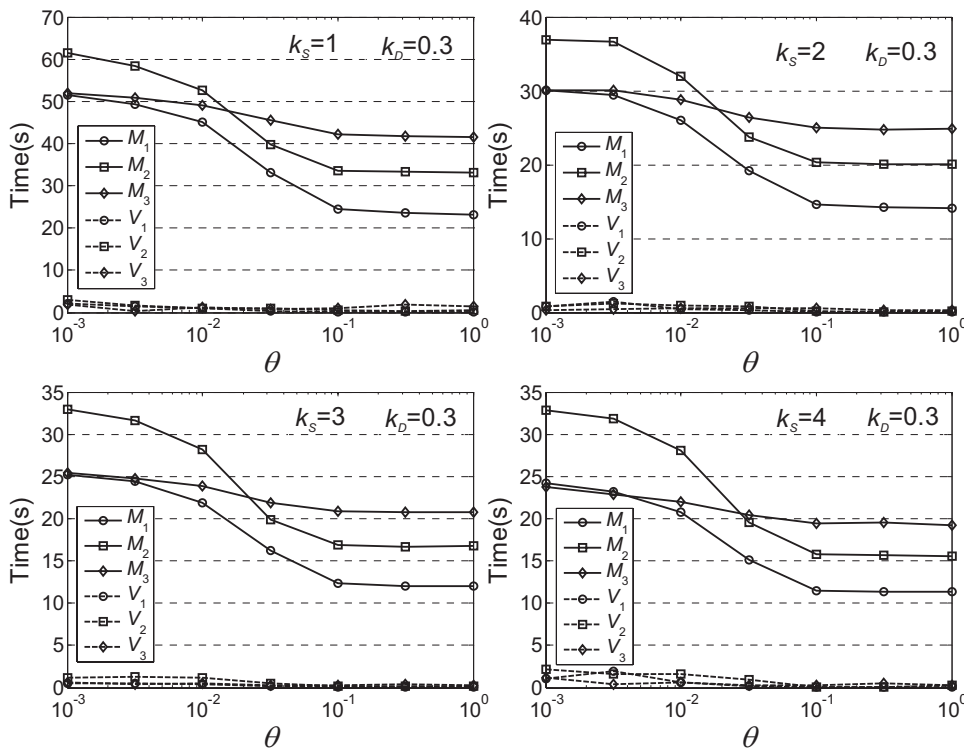


FIG. 6. Mean values and variances of evacuation times against θ when k_D is kept at 0.3 and k_S takes four different values 1, 2, 3, and 4.

the closest exits within a very short time. The modified model is used to simulate pedestrian evacuation in three scenarios with identical internal obstacles but different exits. The simulation results show that the evacuation time is sensitive to the exit position and some model parameters. The degree of familiarity of pedestrians with the information about exits will affect the evacuation time in the case of panic. When doors are uniformly distributed around the building, pedestrians take less time for evacuation regardless of their knowing about the distance to all exits. When doors are not uniformly distributed around the building, providing more doors is helpful if all pedestrians are familiar with the

positions of the exits but useless otherwise. It is also found that blindly following others will lead to an increase of evacuation time.

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