# Relationship between Performance-based Design of Building Exits and State Transition of Pedestrian Flow during Occupant Evacuation

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**ABSTRACT:** A discrete 'social force' cellular automata model is applied to simulate the occupant evacuation in densely occupied buildings. The relationship between the state transition of pedestrian flow and the exit structure, including the exit width *d* and the exit separation *f*, are investigated. Discussions on the appropriate placement of exits and the relationship between the optimal value of *f* and building size will be useful for the performance-based design of building exits.

**KEY WORDS:** cellular automata, occupant evacuation, pedestrian flow, performance-based design of building, fire.

## BACKGROUND AND INTRODUCTION

As part of the continuing investigations on the physics of granular materials [1,2], it is now believed that the diverse phenomena of traffic flow, pedestrian flow, and floating ice [3–5] are related to the nonlinear behavior of granular materials which can exhibit both solid-like and fluid-like behavior [6–8]. These peculiar properties [8,9] give rise to at least three important 'states' in granular flows, namely, dilute flow, dense flow, and the jammed state. The phenomenon of crowding can be considered as a transition from dilute to dense flows and that of jamming is a transition from dense flow to a jammed state. Since interactions among the granular particles are highly nonlinear and characterized by dissipations, which can

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be density and even history dependent, these transitions and their states are still not well understood. Recently, there has been some progress in the understanding of the transition from dense to jammed states [10,11]. However, very little is known about the dilute to dense flow transition. It is considered that the size of the grains [10] is an important characteristic of the dense-to-jammed transition. In contrast, the global scale of the order of the size of the system is important for the dilute-to-dense transitions. For example, a small bottleneck of the size of the system can induce the dilute-to-dense transition [12]. The dilute-to-dense transition is similar to transitions in hydrodynamic flows [13]. Different Reynolds numbers are associated with different flow configurations to characterize the flow as laminar or turbulent. The Reynolds number is a global parameter which scales with the system size. Analogously, in the case of dilute-to-dense transitions, there is also a global scaling parameter.

Movement during an occupant evacuation can also be considered as a kind of discrete flow. Especially when the density of occupants is high, people in the pedestrian flow can do nothing but go with the crowd. Their walking speed is constrained by the other people in the flow; individual ability and psychology play a reduced role in their movements and the occupants act just like granular material. The state of the pedestrian flows can be dilute, dense, and jammed. In dilute flow, occupants can walk at their expected speed, and their individual ability and psychology make individual behavior different from each other. In dense flow, occupants act more like granular material and their walking speeds are restricted by the other occupants. Of greatest interest is the dilute-to-dense transition in pedestrian flow and the relations between the exit design and this state transition.

Pedestrian flow in evacuation has essential differences from the flows of inanimate granular material: (1) The walking speed of occupants is confined to a relatively small range, while particle velocity can be increased endlessly in gravity or some other fields; (2) The forces in granular flow are gravity, friction, etc., while pedestrian flow may be more complex because of various 'social forces' which can be simulated by physical attributes, such as position attraction, attraction and repulsive force caused by nearby occupants, attraction of movement direction, and repulsive force caused by fire; (3) The interactions among the occupants in pedestrian flow are more complex than that among inanimate grains. In the case of granular flow, there are only collision, extrusion, and so on, complying with the deterministic physical rules, while different psychologies of occupants will arouse different behavior: on the one hand, all occupants try to avoid colliding with each other; on the other hand, occasionally they want to gather together with their relatives or follow the crowd; and (4) It is also different in the bottleneck phenomenon. Grains can pile up around the bottleneck. When they pile up to a certain degree, phenomena similar to 'avalanches' occur, namely, a large quantity of grains flow through the exits suddenly. If the occupants pile around the bottleneck, there can be potentially dangerous phenomena such as crushing and trampling. But sometimes occupants queue for evacuation at the bottleneck or move up and down uneasily [14]. Especially, in an evacuation with the intervention of staff, the avalanche phenomenon will seldom happen.

## MODEL DESCRIPTION

Along with the increase in population size and social activity, social publics, such as shopping mall, student eatery, gymnasium, stadium, subway, etc., often become crowded or jammed, especially in the case of an emergency, such as a fire. This article focuses on human behavior [15–18] and specifically the relationship between exit design in a densely occupied room and state transition of the pedestrian flow during an evacuation. A two-dimensional cellular automata model based on an existing cellular automaton model [19] and continuous 'social force' model [14,20–23] is used.

Generally, the occupants try to move quickly toward the exits, avoid colliding with each other and sometimes go with the crowd during an emergency. The essence of the model are discrete 'social forces,' which describe various 'external forces' and 'internal forces' including position attraction, attractive and repulsive forces caused by surrounding occupants, movement direction and fire, etc.

A network of cells is applied in this model. Each cell corresponds to $0.4 \times 0.4\,\text{m}$ [19], which is the typical space occupied by an occupant in a dense crowd. In this study, 0.4 m is regarded as one unit, namely, the dimensionless size of an occupant is 1 and the dimensionless size of the room is the actual size divided by 0.4 m. Empirically, the occupants' walking velocity varies between 0.5 and 1.5 m/s [14] according to the individual's ability. Here, 0.8 m/s is adopted as the average walking speed, which is a typical value in a dense crowd. Thus, one time-step (ts) in the model corresponds to 0.5 s, i.e., $1\,\text{ts} = 0.5\,\text{s}$. The change of walking speed with crowd density during evacuation is not considered.

In a von Neumann neighborhood, four directions are taken into account, i.e., up, down, left and right, while in a Moore neighborhood, eight directions including diagonal directions are considered. In the current model, the von Neumann neighborhood is adopted to determine the movement direction of occupants because four directions are enough for describing the movement of evacuees. Although a Moore neighborhood is more accurate, it is not as simple as the von Neumann neighborhood. The following formula is applied to determine the route choice:

$$p_{ij} = N\exp(k_S S_{ij})\exp(k_F F_{ij})\exp(k_R R_{ij})\exp(k_A A_{ij})\exp(k_D D_{ij})(1 - n_{ij}) \quad (1)$$

where $p_{ij}$ denotes the probability of moving to the cell $(i,j)$; $n_{ij} = 1$ denotes that the cell $(i,j)$ is occupied by a occupant at the time of $t$, otherwise, $n_{ij} = 0$; the parameter $N$ is introduced as:

$$N = \left[\sum_{(i,j)} \exp(k_S S_{ij})\exp(k_F F_{ij})\exp(k_A A_{ij})\exp(k_D D_{ij})(1 - n_{ij})\right]^{-1} \quad (2)$$

where $S_{ij}$ and $k_S$ denote position attraction and its influence coefficient for cell $(i,j)$, respectively; $R_{ij}$ and $k_R$ denote the repulsive force of the occupants around and its influence coefficient for cell $(i,j)$, respectively; $A_{ij}$ and $k_A$ denote attraction of the occupants around and its influence coefficient for cell $(i,j)$, respectively; $D_{ij}$ and $k_D$ denote attraction of movement direction and its influence coefficient for cell $(i,j)$, respectively; $F_{ij}$ and $k_F$ denote the fire repulsive force and its influence coefficient for cell $(i,j)$, respectively; where, $k_S$, $k_A$, $k_D \geq 0$, $k_F$, $k_R \geq 0$.

$S_{ij}$ is determined by the choice of safety exits. In general, the nearer to the exit, the greater the value this parameter is for a cell. The simple formula is:

$$\begin{aligned} S_{ij} = &\max_{(i,j)}\left\{\min_{(ie_k, je_k)}\left\{\sqrt{(ie_k - i)^2 + (je_k - j)^2}\right\}\right\} \\ &- \min_{(ie_k, je_k)}\left\{\sqrt{(ie_k - i)^2 + (je_k - j)^2}\right\} \end{aligned} \quad (3)$$

where $(ie_k, je_k)$ denotes the coordinates of each exit. The second item on the right of the equation denotes the minimum of the distance between $(i,j)$ and each exit. The first item is the maximum of the above values. Thus, the position attraction of the most distant cell from the closest exit is 0. The disadvantage of this formula is that it can only compute the case of a building without barriers. As far as a room with barriers is concerned, the following method is used: the danger grade of each exit is prescribed as 0, and the danger grade of each cell, except for walls and barriers, will be updated simultaneously at each time step (the values of the walls and barriers are certain maximum values). If a cell's danger grade is greater than the minimum value for the four adjacent cells, then the danger grade will be the sum of one and this minimum value at the next time step. Each cell's opposite attraction is the difference between the cell's danger grade and the maximum danger grade of all cells. Adding this opposite attraction to the position attraction obtained from Formula (3), a new value of $S_{ij}$ is obtained, which is used in the case of the room with barriers.

During the process of evacuation, occupants always try to maintain a distance between each other to avoid collision. The occupants within a radius of $r_1$ are considered to have such repulsive forces $R_{ij}$; the closer to each other the individuals are, the greater this value becomes. The occupants within a radius of $r_2$ have an attribute $A_{ij}$, which describes the phenomenon of gathering together. The occupants within a radius of $r_3$ have an attribute $D_{ij}$, which describes the phenomenon of going with the crowd. The value of each coefficient, which can be changed during the evacuation process, is the key factor to determine the dominant forces.

The local rules of the model are listed below:

1. Calculate the moving probability of each cell.
2. Each occupant chooses one of the adjacent cells as an objective for the next time step depending on the moving probability.
3. For each cell where more than one occupant desires entry, randomly assign it to one of them; the other occupants remain where they are. In this model, every competitor is considered to have the same probability.
4. In order to avoid a completely deterministic model, a random speed reduction rule is introduced: Each person who has decided to move is given a probability to remain where they are, with a 5% probability applied. This was derived from testing and experience with the model.
5. After parallel updating of each occupant during each time step, compute each cell's moving probability if necessary.
6. Cycle through the previous steps until all the occupants finish their evacuation.

Attractive and repulsive forces are used to simulate the relationship between occupants and the building and the relationship among occupants. This method is derived from Helbing's [20] social force model; Rule 4 can simulate the 'randomness' (i.e., inability to predict precisely) in the individual's response. This concept comes from the random slowdown rule in traffic flow.

## SIMULATION CASES

In order to find out the relationship between the exit design and the state transition of pedestrian flow. The following cases are simulated.

## Single Exit

A room with only one exit is considered. The dimensionless length of the scenario $L$ is 100, and the width $D$ is 15, 20, 25, and 30, respectively. Since the areas close to the doorframe or wall cannot be used in a real evacuation, the size of these areas is subtracted from the actual size to yield the efficient size. In this model, only the efficient size is considered. Exit $d$ is located at the middle of $D$. The density of occupants in a random distribution is greater than 0.5. Figure 1 is the case of $L = 100$, $D = 30$, $d = 2$ with 1534 people.

## Two Exits

*Optimal Exit Separation f*

In order to find out the optimal value of the exit separation $f$, a scenario of $L = 100$, $D = 24$ with a symmetrical layout of two exits is considered. There are 1415 people randomly distributed in the room with a density of 0.590 (Figure 2). Another scenario is $L = 18$, $D = 14$ with 200 people randomly distributed in the beginning.

*State Transition Point*

A symmetrical layout of two exits is applied in a room with $L = 100$, $D = 20$, 25, 30, and 35, respectively. Evacuation with optimal exit

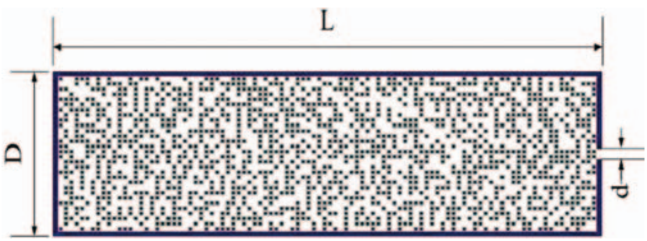


***Figure 1.*** *Initial distribution: L = 100, D = 30, d = 2, 1534 people. (The color version of this figure is available on-line.)*

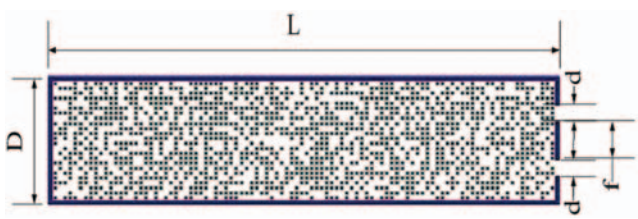


***Figure 2.*** *Initial distribution: L = 100, D = 24, d = 3, f = 8, 1415 people. (The color version of this figure is available on-line.)*

separations corresponding to different widths of the room is considered, viz. $f = 6$, 7, 10, and 11, respectively.

## RESULTS OF SIMULATION

### Single Exit

When $d = 1$ or 2 (small value of the exit width), the occupants assemble at both sides of the exit all the time until almost all the occupants have evacuated the room, which is similar to the phenomenon in the case of granular flow. But there is no 'avalanche' phenomenon. When the initial route is blocked, the evacuees wait or change to another cell. The size of the peak formed during the evacuation process (location of occupied cells furthest from the exits) reduces gradually from 100 to 0. The interspaces (unoccupied cells) among occupants, which are randomly distributed in the beginning, have a trend of moving toward the edge of the peak along with the evacuation. Finally, they are distributed only in the neighborhood of the exit and the edge of the peak (Figure 3(a)); only the occupants in these areas have control over their direction of movement. The middle part of the pedestrian flow with a local density of 1 has almost no interspaces. Hence, the occupants in this area have almost no control over their movement and can only follow those ahead of them. Along with the increase of the exit width, after $d = 6$, the distribution of interspaces becomes uniform and there is no phenomenon of distributing only in the neighborhood of the exit and the edge of the peak (Figure 3(b)). Thus the evacuation efficiency is distinctly improved, taking on a state of dilute flow. The gathering at both sides of the exit also becomes less obvious, only happening in the beginning.

With the increase in the exit width $d$, the evacuation time and the total flux $Q$ increase accordingly, but the flux per unit width $q$ decreases. This is the same as previous results by other researchers [24]. These data are linearly fit in segments as shown in Figure 4. When $d < 7$, $q = 1.02501 - 0.07842d$; When $d > 7$, for different $D$, the data on $q$ are fit into a set of beelines with different slope, and the average is: $q = 0.580705 - 0.00915d$. The point of intersection is $(6.414104, 0.522016)$, which is the critical point of dilute-to-dense state transition of pedestrian flow. It is consistent with the phenomena being observed from dynamic play.

Whether these results are suitable for engineering design needs to be checked in practice. According to the Building Fire Protection Code of China (GBJ16-87), in public sites such as an exhibition hall, cinema, auditorium, etc., if the number of occupants is under 1200, the total width of all the exits should be at least 0.85 m/100 people; if the number of occupants

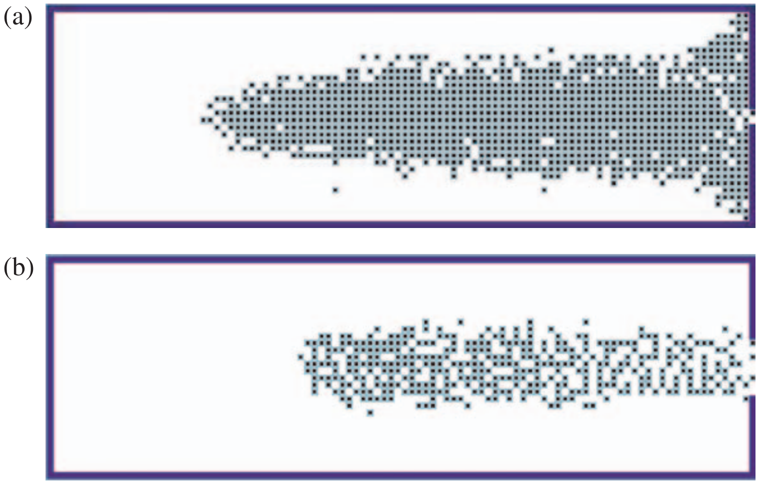


*Figure 3. Distribution of occupants at 500 ts when: (a) d = 2 and (b) d = 8. (The color version of this figure is available on-line.)*

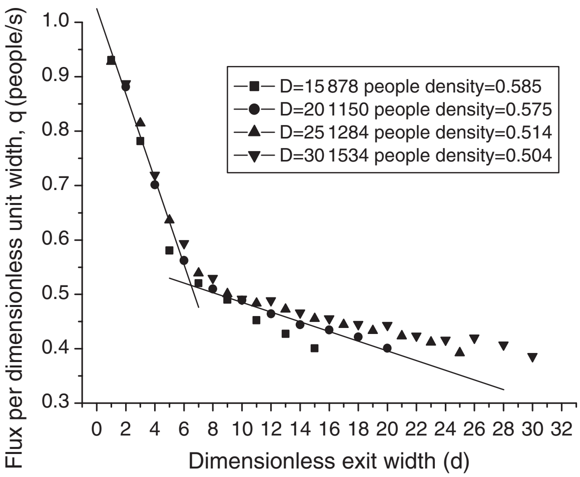


*Figure 4. Relationship between the flux per unit width and the exit width in the case of single exit.*

is between 1200 and 2500, the total width of all the exits should be at least 0.65 m/100 people.

In the case of 878 people, the exit width should be at least $0.85 \times (878/100) = 7.463$ m. For the case of 1150, 1284, and 1534 people, the exit width should be larger than 9.775, 8.346, and 9.971 m, respectively.

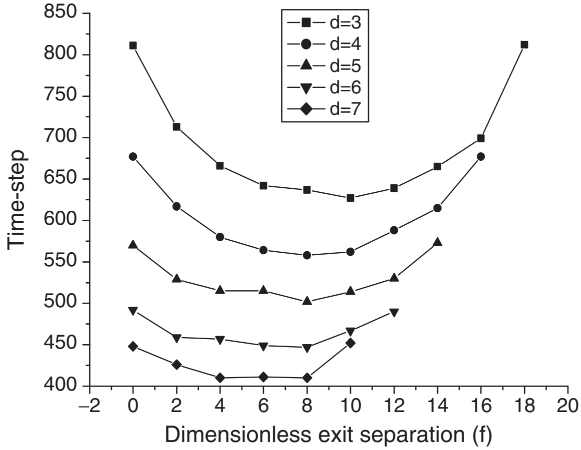


***Figure 5.*** *Relationship between the exit separation and the evacuation time with different exit widths.*

These values are all larger than the critical point, $d = 6.414$ (2.567 m) obtained in this study, so the pedestrian flow is a dilute flow which is safe for evacuation. The barriers such as seats and stages are not taken into account in the current scenarios. In practice, those barriers will hinder occupant evacuation. So the design value according to the code is suitable in practice.

## Two Exits

### *Design for Optimal Exit Separation f*

In the case of the room $100 \times 24$, for different values of $d$, the optimal value of $f$ is about 8 (Figure 5); In the case of the room $18 \times 14$, the optimal value of $f$ is about 4 for different values of $d$. Therefore, the optimal value of $f$ is assumed related to the width of the whole wall $D$ and does not vary with the exit width $d$ and $f \approx 0.3D$ is the optimal value.

When $f = 8$, interspaces (the unoccupied cells) are distributed at the edge of the peaks and the neighborhood of the exits, and there are only a small number of interspaces in the middle of each pedestrian flow. Along with the process of evacuation, the two peaks gradually merge into one. But there is a 'line' with many interspaces mid-way between the two exits (Figure 6(a)). This is called the 'interspaces line'. Occupants on this line are more active, which is of great benefit to the evacuation. Near the end of the evacuation process, there are two independent peaks again (Figure 6(b)). If the value of $f$ decreases, the speed of changing from two peaks to one peak is much faster, the 'interspaces line' becomes less apparent, and it does not change to

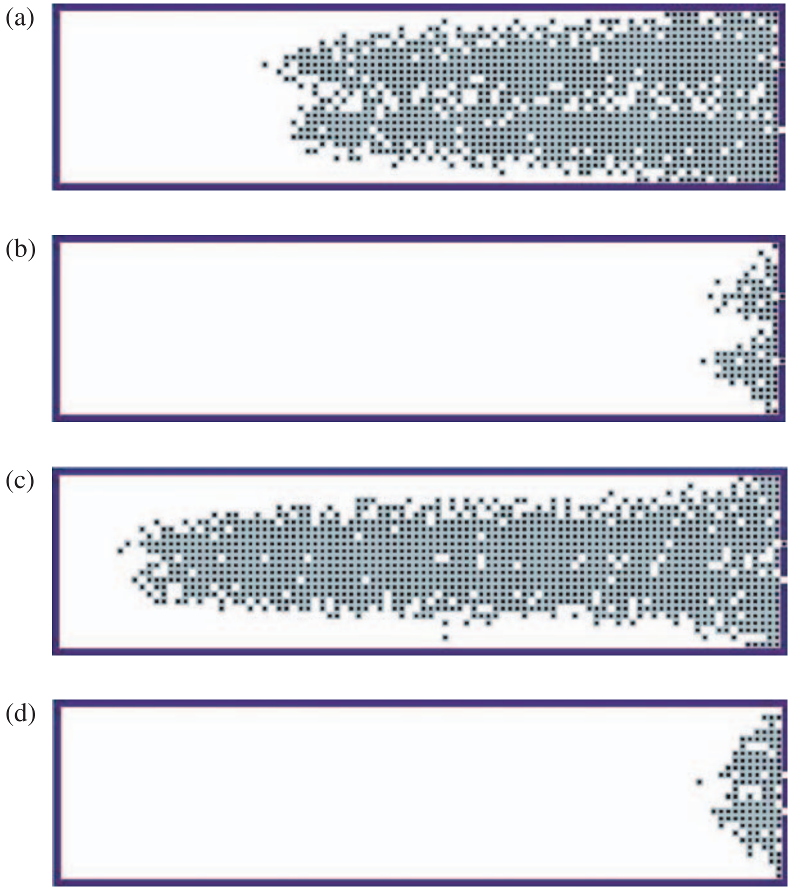

***Figure 6.*** *Distribution of the occupants with different f: (a) f = 8, 300 ts; (b) f = 8, 1380 ts; (c) f = 4, 200 ts; and (d) f = 4, 1400 ts. (The color version of this figure is available on-line.)*

two separate peaks again (see Figures 6(c) and (d)). If the value of $f$ is decreased still further, the manner of pedestrian flow is the same as that in the case of a single exit, i.e., there is only one peak all the time.

*Critical Point of State Transition in the Case of Two Exits*

As shown in Figure 7, each segment of the flux per unit width versus exit width is linear. The results are listed in Table 1. The case of $d = 1$ is not considered because the flux per unit width is obviously low, and the pedestrian flow takes on a jamming state, with (4.47518, 0.57862) being the critical point of dilute-to-dense state transition in the case of two exits.

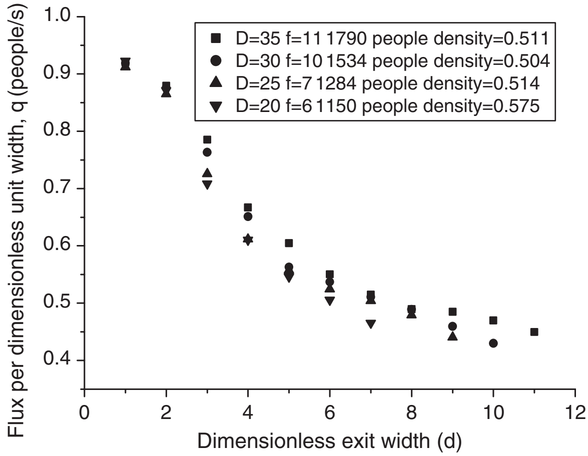


***Figure 7.*** *Relationship between the flux per unit width and the exit width in the case of two exits.*

***Table 1. Linear fit in two segments of flux per unit width vs. the exit width in the case of two exits.***

| Dimensionless width $D$ | First segment | Second segment | Intersection point |
|---|---|---|---|
| 20 | $q = -0.13041d + 1.12129$ | $q = -0.04046d + 0.74857$ | (4.14364, 0.58092) |
| 25 | $q = -0.12691d + 1.11476$ | $q = -0.02789d + 0.69621$ | (4.22692, 0.57832) |
| 30 | $q = -0.11224d + 1.10001$ | $q = -0.02631d + 0.69554$ | (4.70697, 0.57170) |
| 35 | $q = -0.10613d + 1.09544$ | $q = -0.02344d + 0.69661$ | (4.82320, 0.58355) |
| Average | | | (4.47518, 0.57862) |

## CONCLUSIONS

In this study, the movement of occupants during evacuation is determined by several 'social forces.' The position attraction reflects the relationship between occupants and building structure; the attraction and repulsive force of the surrounding occupants describe the behavior of gathering together and maintaining a distance between each occupant to avoid collision, respectively; the attraction of a moving direction embodies the psychology of going with the crowd; the fire repulsive force depicts the relation between occupants and fire.

A two-dimensional cellular automata model is applied in the performance-based design of building exits. Useful conclusions are obtained that are suitable for densely occupied social public structures, such as an exhibition hall: (1) For the building with two exits, the optimal value of the exit separation $f \approx 0.3D$ and does not vary with the exit width. In practice, the requirement of symmetrical layout should also be taken into account; (2) The value of the exit width influences the state of pedestrian flow. The critical state transition points in the case of single exit and two exits are about 6.4 and 4.5 units of width of each exit, respectively. The exit width should be larger than (or at least equal to) the above critical values in practice.

## NOMENCLATURE

$p_{ij}$ = the probability of moving to the cell $(i, j)$
$S_{ij}$ = position attraction of cell $(i, j)$
$k_S$ = influence coefficient of position attraction
$R_{ij}$ = repulsive force of occupants around the cell $(i, j)$
$k_R$ = influence coefficient of repulsive force
$A_{ij}$ = attraction of occupants around the cell $(i, j)$
$k_A$ = influence coefficient of attraction of occupants around
$D_{ij}$ = attraction of movement direction of cell $(i, j)$
$k_D$ = influence coefficient of attraction of movement direction
$F_{ij}$ = fire repulsive force of cell $(i, j)$
$k_F$ = influence coefficient of fire repulsive force
$(ie_k, je_k)$ = the coordinates of each exit
$d$ = dimensionless exit width
$D$ = dimensionless total width of the side with exits
$f$ = dimensionless exit separation
$q$ = flux per dimensionless unit exit width (people/s)
$Q$ = total flux (people/s)

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