Logit-based exit choice model of evacuation in rooms with internal obstacles and multiple exits*

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A logit-based discrete choice model is proposed to study the exit choice behaviour of evacuees in rooms with internal obstacles and multiple exits. Several factors influencing the exit choice behaviour, including the information obtained by evacuees, the tendency of following others, the visibility and familiarity of exits and the physical conditions of nearby exits, are considered. Evacuees are allowed to re-select their target exits for minimizing the perceived disutility during evacuation process. Numerical results from applying the model to cellular automata simulation of evacuation are presented and the effects of some model parameters on evacuation time are investigated.

Keywords: exit choice, evacuation, logit-based discrete choice, cellular automata

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1. Introduction

Pedestrian flow is an important research topic in urban traffic studies. Pedestrian flow exhibits complex and variable patterns of behaviour in some specific scenarios, such as panic evacuation, roadway crossing, and bidirectional movement. In general, two types of methods are used to model pedestrian flow, namely, microscopic and macroscopic ones. In the former, pedestrians are regarded as discrete individuals in computer simulation.[1−11] The latter is usually applied to the case of a large crowd. In this method, the crowd is treated as a whole and the fluid theory related methods are used to explore the aggregate behaviour.[12−14]

Studying the behaviour of pedestrians during evacuation is extremely important in emergency management. Many pedestrian evacuation models have been developed to help the designers and the managers of various buildings and public places improve the evacuation facilities and make the rules and regulations of evacuation become perfected.[1,4,8−11,15−19]

One of the critical behavioural reactions for pedestrians, which may affect their evacuation processes, is the choice of exits. This decision making is influenced by many factors, such as personal characters, building geometry, and observations concerning the dynamic evacuation situation. Once pedestrians cannot appropriately select exits for leaving, a phenomenon where most pedestrians run away to few exits, whereas some exits are used by few pedestrians, is likely to occur, and leads to a longer evacuation time for most pedestrians. In addition, studying the exit choice behaviour of pedestrians is also the foundation, on which the so-called intelligent guide sign that is used to guide pedestrian evacuation can be developed. Through the intelligent guide sign, evacuees can obtain dynamic useful information for evacuation, such as the position of all efficient exits, the congestion degree of these exits and the length of evacuation time that has passed.

In some evacuation models (e.g. Refs. [4] and [15]), it is assumed that all evacuees head straight to the nearest exit. This assumption is unrealistic in many occasions,[20] and is likely to lead to more evacuation time than the actually experienced one. In fact, the disutility experienced by a pedestrian for leaving from an exit, is determined by not only his or her velocity and the distance to the exit, but also some external factors, such as congestion degree around the exit and the width of the exit. His or her decision will be affected by what has been seen in the environment and what has been formulated in his or her mind. In addition, the decision is affected by other pedestrians' actions, hence the interactions among pedestrians should also be considered in modeling the exit choice of pedestrians in rooms with multi-exits.

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The exit choice behaviours of pedestrians have been studied recently. In Ref.[21] a behavioural feature, which concerns the response of evacuees to exit selection and re-direction, was developed and implemented into the building EXODUS evacuation model. The behaviour is not simply pre-determined by user as part of initialization process, but involves evacuees taking decisions based on their previous experiences and their information available in the whole process of evacuation. When evacuating through fire environments, the presence of smoke may lead evacuees to adapt their evacuation strategy through the adoption of another exit. In Ref. [22] this type of adaptive behaviour within the building EXODUS evacuation model was introduced through enabling evacuees to make decisions concerning the selection of the most viable available exit during an evacuation involving fire. Lo *et al.* presented a game theory approach to model evacuees' exit choice.[23] A two-player, non-cooperative, zero sum game was envisaged between the crowd of evacuees seeking exit to minimize the expected travel time and a 'virtual entity' imposing the blockage influence on the evacuees to maximize the expected travel time. Ehtamo *et al.* proposed a game theoretic model for evacuees to choose their exits.[24] The model is based on the game theoretic concept of players' best response functions, and a fixed point of these functions determines the Nash equilibrium of the game.

During evacuation, the exit choice is strongly related to the pedestrians' perception and cognition to disutility. Pedestrians cannot accurately estimate the disutility, especially when the exits are invisible for them. In the present paper, the logit-based discrete choice model is used to formulate the stochastic exit choice behaviour of evacuees in rooms with internal obstacles and multiple exits. The disutility of pedestrians to each exit varies with their movement, and pedestrians are able to react to the new situation. The disutility of a pedestrian to an exit is then determined by the feasible route distance, the width of the exit, and the number of pedestrians selecting the same exit. This exit choice model is embedded in a microscopic simulation of evacuation process for numerically investigating the complex pedestrian flow patterns.

2. Logit-based exit choice model

We consider a scenario, in which a set of pedestrians, N, attempts to evacuate from a room with internal obstacles and a set of exits, E. During evacuation, there is a set of $S_i^t(\subset E)$ exits available for pedestrian i at time t, that is, at time t pedestrian i can select one of exits of this set to leave the room. Then, E/S_i^t is the set of unavailable exits for pedestrian i at time t. This set includes the exits unfamiliar to pedestrian i and those for pedestrian i to reach difficultly at time t due to hard conditions along routes to the exits (e.g. fire, toxic gas and smoke).

We further divide the set S_i^t into three subsets, i.e. $S_i^t = \{S_i^{1t}, S_i^{2t}, S_i^{3t}\}$, where S_i^{1t} is a subset of exits that are visible to pedestrian i at time t, S_i^{2t} a subset of exits that are familiar but invisible to pedestrian i at time t, and S_i^{3t} a subset of exits whose position information is obtained by pedestrian i at time t through some guides provided by emergency signs or neighbouring pedestrians. Here, the behaviour that a pedestrian learns the position information of an exit from the actions of other pedestrians and then selects the exit, can be considered as a collecting effect.[2,4] It can be seen from these definitions that factors influencing exit choice, including the pedestrians' familiarity with the layout of the structure, the visibility of exits, the conditions along routes to exits and the exit information,[21−24] will be taken into account in our study.

In a room with internal obstacles and multiple exits, it is generally difficult for a pedestrian to find an optimal target exit within a short time. This is particularly true in a urgent case. Pedestrians cannot accurately estimate the disutility due to the effects of unobserved attributes and characteristics. Thus, we assume that pedestrians select target exit according to their perceived disutility. The perceived disutility $\widehat{T}_{ij}^{\,t}$ that pedestrian i pays for leaving the room through exit j at time t, is then expressed as

$$\widehat{T}_{ij}^{\,t} = T_{ij}^t + \xi_{ij}^t, \tag{1}$$

where T_{ij}^t is the expected value of $\widehat{T}_{ij}^{\,t}$, and ξ_{ij}^t represents a random error term. T_{ij}^t comprises the free moving disutility $\tau_{ij}^t(r_{ij}^t, v_i)$ and the congestion disutility $\varphi_{ij}^t(\lambda_j^t, \mu_j)$ of pedestrian i to exit j at time t, i.e.

$$T_{ij}^t = \tau_{ij}^t(r_{ij}^t, v_i) + \phi_{ij}^t(\lambda_j, \mu_j), \tag{2}$$

where r_{ij}^t is the route distance to exit j at time t, v_i the speed of pedestrian i, λ_j the arrival rate of pedestrians at exit j, and μ_j the leaving rate of pedestrians from exit j.

Suppose that all random terms ξ_{ij}^t in a subset of available exits are independent and identically

distributed Gumbel variables with zero mean. According to the concepts of random utility and utility maximisation,[25] at equilibrium the probability P_{ij}^{kt} that pedestrian i selects exit j of class-k subset at time t, is governed by the following logit formula:

$$P_{ij}^{kt} = \frac{\exp(-\theta_i^k T_{ij}^t)}{\sum\limits_{l \in S_i^{kt}} \exp(-\theta_i^k T_{il}^t)}, \quad j \in S_i^{kt}, \tag{3}$$

where parameter θ_i^k (≥ 0) $(k = 1, 2, 3)$ is the disutility perception variation of pedestrian i for class-k exit. Higher θ_i^k-value means smaller perception variation for pedestrian i. This parameter reflects the familiarity degree of pedestrians to some class of exits. Clearly, the relation $\theta_i^1 \geq \theta_i^2 \geq \theta_i^3$ holds. When an exit is visible to a pedestrian, the pedestrian can estimate the route distance to the exit and know the degree of congestion near the exit.

Let the probability that pedestrian i selects exits in subset $S_i^{kt}(k = 1, 2, 3)$ at time t be Q_i^{kt}, then we will define

$$Q_i^{kt} = \frac{M_i^{kt}}{\sum\limits_{l=1}^{3} M_i^{lt}}, \tag{4}$$

$$M_i^{kt} = \begin{cases} \exp\left(-\delta_i^k \min\limits_{j \in S_i^{kt}} \{T_{ij}^t\}\right), & S_i^{kt} \neq \phi, \\ 0, & S_i^{kt} = \phi, \end{cases} \tag{5}$$

where parameter δ_i^k (≥ 0) $(k = 1, 2, 3)$ is the sensitivity of pedestrian i to class-k exit. The relation $\delta_i^1 \leq \delta_i^2 \leq \delta_i^3$ holds generally. This implies that pedestrians have different preferences for selecting each class of exits. They prefer to select visible exits and have more preferences to familiar exits than learned exits. The visibility of exits greatly influences the pedestrians' decision making, as the information about congestion and the physical conditions near an invisible exit are limited.[21] It is true that evacuees tend to adopt familiar alternatives for reducing the risk.[20]

Then, the probability R_{ij}^t that pedestrian i selects exit j at time t, is given by

$$R_{ij}^t = Q_i^{kt} P_{ij}^{kt}. \tag{6}$$

It can be seen from the above expressions that the exit choice model proposed in Ref. [24] is covered by our model when the priority of each class of exits is determined and the $\theta_i^k \to +\infty$ $(k = 1, 2, 3)$.

The above exit choice model can be embedded in some microscopic simulations of pedestrian flows,[1,2,4,7–11] to study the exit choice behaviour of pedestrians. When the exit choice behaviour governed by expression (6) is added into the cellular automata model in Ref. [10], T_{ij}^t can be computed by

$$T_{ij}^t = \begin{cases} \dfrac{\alpha d_{ij}^t + \beta N_{ij}^t}{w_j}, & t > 1, \\ \dfrac{\alpha d_{ij}^t}{w_j}, & t = 1, \end{cases} \tag{7}$$

where α and β are two positive parameters, and d_{ij}^t is the most feasible route distance of pedestrian i to exit j at time t, N_{ij}^t is the number of pedestrians who select exit j at time $t-1$, and w_j is the width of exit j. In Ref. [10] was provided an algorithm to compute the most feasible distance, in which d_{ij}^t is the weighted sum of the minimal number of lattice sites experienced by the pedestrian i leaving the room through exit j, when the movements in horizontal or vertical direction and in all eight directions are permitted.

In Ref. [10], it was assumed that pedestrians only selected target exits for leaving at the initial time of evacuation. In reality, however, pedestrians are likely to re-select their target exits in the evacuation process, according to their positions at that time. Thus, we here prescribe that pedestrians select their target exits every γ time increments. When all exits belong to one class, the disutility is the route distance to exits and pedestrians are only allowed to select target exits at initial time, the exit choice model is identical with that in Ref. [10]. In the next section, we will apply the above model to a cellular automata micro-simulation of evacuation process.

3. Simulation results

Suppose that 400 pedestrians attempt to evacuate from a room with five exits, as shown in Fig. 1. The space of the room is discretized into square lattices, and the size of each lattice site is 0.4×0.4 m^2. Each time step of the simulation is 0.3 s, which corresponds to a walking speed of 1.33 m/s approximately. In each time step the positions of all pedestrians are updated in a random sequence. The widths of the five exits are 2, 1, 2, 1 and 3 lattice sites, separately. The size of the room is marked in Fig. 1(a) (unit: lattice site). We use the floor field cellular automata model proposed in Ref. [10] to conduct the pedestrian evacuation simulation, in which the weighted coefficient in the most feasible route distance takes the value of 0.5, and the two sensitivity parameters for scaling the static and the dynamic floor fields are set to be 3 and 0, respectively. Exits 1, 2, 3, 4 and 5 are only visible

for pedestrians in regions I, II, III, IV and V, respectively. An exit of a region is not directly visible for pedestrians in other regions.

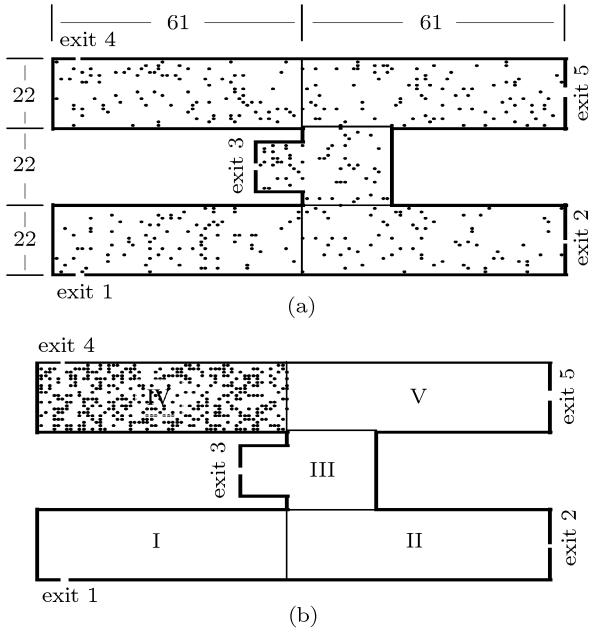


Fig. 1. Simulation scenario and initial pedestrian distribution. (a) 400 pedestrians are randomly distributed in the whole space of the room. (b) 400 pedestrians are randomly distributed in region IV near exit 4.

Suppose that there is an emergency guide sign to provide pedestrian i with the information about the position of only one exit at time t. Thus, the set S_i^{3t} is determined by

$$S_i^{3t} = \left\{ \arg \left\{ \min_{j \in E} \{F_{ij}^t\} \right\} \right\}, \tag{8}$$

where

$$F_{ij}^t = \begin{cases} d_{ij}^t + \eta \dfrac{N_{ij}^t}{w_j}, & t > 1, \\ d_{ij}^t, & t = 1. \end{cases} \tag{9}$$

In expression (9), η is a positive parameter. Higher η means that the emergency guide sign attaches more importance to the degree of congestion near exits and the width of exits.

First, we examine the effects of the parameters $(\delta^1, \delta^2, \delta^3)$ in expression (5) and the time period γ of re-selecting exits on pedestrian evacuation. Two cases are investigated in the simulation. In case one, each pedestrian is familiar with partial exits, and the familiar exits are randomly determined for each pedestrian at initial time. In case two, each pedestrian is familiar with all exits. All pedestrians are randomly distributed in the whole space of the room at initial time. The model parameters are given as follows: $(\theta^1, \theta^2, \theta^3) = (1.0, 0.1, 0.01)$, $\gamma = 10$, $\alpha = 0.3$, $\beta = 0$ or 0.5, and $(\delta^1, \delta^2, \delta^3) = (0.1, 0.1 + 0.02x, 0.1 + 0.04x)$.

Figure 2 depicts the average evacuation time of all pedestrians against the x-value varying from 1 to 15, in the two cases with $\beta = 0$ or 0.5. Note that the x-value represents the preference difference for each class of exits to a certain extent.

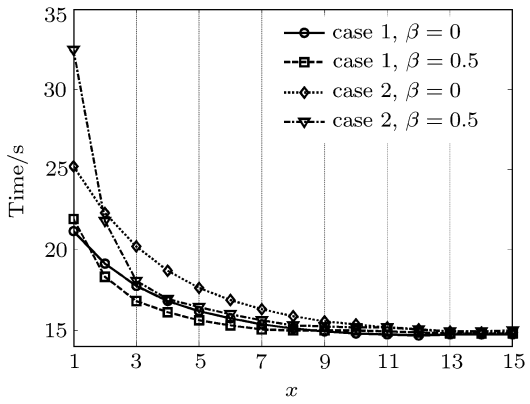


Fig. 2. Average evacuation time of all pedestrians against x-value.

It can be seen that for the four groups of data, the evacuation time decreases with the increase of x-value. In each case, when x-value is less than a certain value, larger β-value corresponds to longer evacuation time; however, when x-value is larger than the value, larger β-value corresponds to smaller evacuation time. This indicates that when pedestrians show unobvious preference difference for each class of exits, they need consider only the route distance to each exit at each re-selection of exits for leaving the room quickly, and when they show more obvious preference difference for each class of exits, they need consider not only the route distance to each exit, but also the width of exits and the number of pedestrians selecting each exit. An interesting finding is that for each β-value, the pedestrians' familiarity to more exits may lead to more evacuation time. With the continue increasing of x-value, the evacuation times become identical, regardless of the case and the β-value.

Figure 3 displays the average evacuation time of all pedestrians against the γ-value varying from 2 to 30, when $(\theta^1, \theta^2, \theta^3) = (1.0, 0.1, 0.01)$, $\alpha = 0.3$, $\beta = 0$ and 0.5, and $(\delta^1, \delta^2, \delta^3) = (0.05, 0.1, 0.15)$. It can be seen that for the four groups of data, as the time period of re-selecting target exits increases, the evacuation time declines. It indicates that frequently re-selecting exits may increase pedestrians' evacuation time. Varying γ-value does not affect the phenomena

that familiarity with more exits leads to more evacuation time, and pedestrians' exit choice, based on the route distance to exits, the number of pedestrians selecting each exit and the width of exits, has them leave the room quickly.

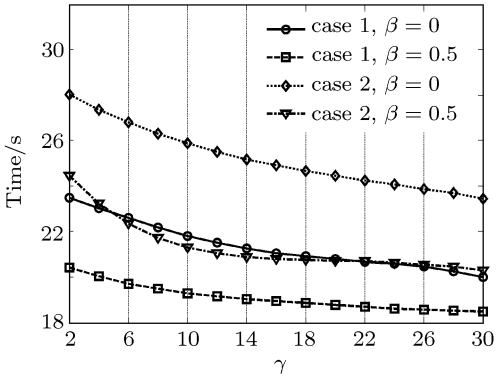


Fig. 3. Average evacuation time of all pedestrians against time period γ.

We then study the effects of the parameter η in expression (9) and the initial distribution of pedestrians on evacuation. Let $(\theta^1, \theta^2, \theta^3)$=(1.0, 0.1, 0.01), $\gamma = 10$, $\alpha = 0.3$, $\beta = 0.2$, and $(\delta^1, \delta^2, \delta^3)$=(0.15, 0.2, 0.1), (0.15, 0.2, 0.15), (0.15, 0.2, 0.2), (0.1, 0.15, 0.05), (0.1, 0.15, 0.1) and (0.1, 0.15, 0.15). Note here that the δ^3-value may be less than the values of δ^1 and δ^2. This means that pedestrians believe the information provided by the emergency guide sign very much, and then prefer to select class-3 exits. Figures 4 and 5 show the average evacuation time of all pedestrians against the parameter η, when all pedestrians are randomly distributed in the whole space of the room, and region IV at initial time, separately (see Fig. 1).

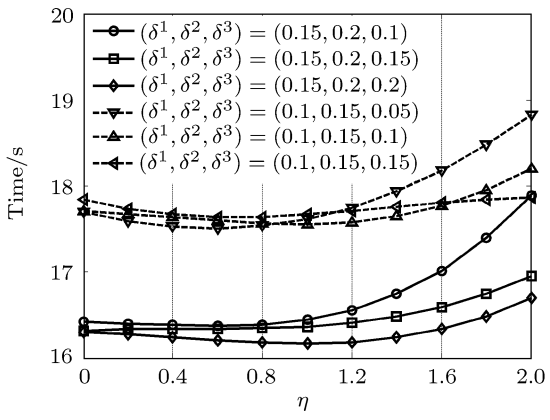


Fig. 4. Average evacuation time of all pedestrians against parameter η, when all pedestrians are randomly distributed in the whole space of the room.

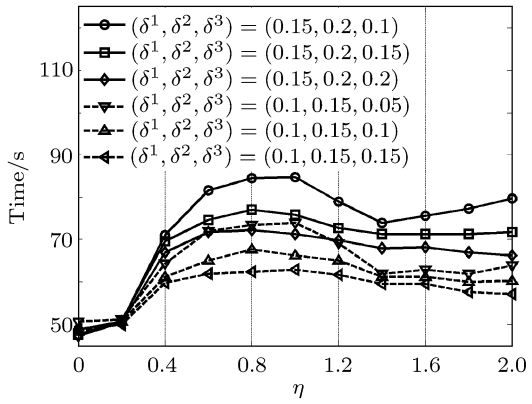


Fig. 5. Average evacuation time of all pedestrians against parameter η, when all pedestrians are randomly distributed in region IV.

When all pedestrians are randomly distributed in the whole space at initial time of the simulation, for all the six groups of data, the evacuation time changes a little if the η-value is not more than 1.0, and increases otherwise (Fig. 4). For fixed δ^1 and δ^2, a smaller δ^3 leads to a more obvious increase of evacuation time. For each η-value, when all elements in $(\delta^1, \delta^2, \delta^3)$ decrease, the evacuation time ascends. This result shows that less considering the difference among the three classes of exits can produce more evacuation time.

When all pedestrians are randomly distributed in region IV at initial time of the simulation, more complex phenomena are revealed (Fig. 5). For all the six groups of data, the evacuation time changes nonmonotonically with the η-value. For fixed δ^1 and δ^2, the nonmonotone becomes more obvious with δ^3-value decreasing. For η-value not larger than 0.2, the varying $(\delta^1, \delta^2, \delta^3)$ has few effects on the evacuation time. When η-value exceeds 0.2, however, the evacuation time declines as all elements in $(\delta^1, \delta^2, \delta^3)$ decrease. This shows that less considering the difference among the three classes of exits can lead to reducing evacuation time in this scenario. Thus, different initial pedestrian distributions may result in inverse evacuation consequence although rational behaviour is assumed.

Finally, we examine the evolutionary process of the number of pedestrians selecting each exit during evacuation. Let $(\theta^1, \theta^2, \theta^3) = (1.0, 0.1, 0.01)$, $\gamma = 10$, $\alpha = 0.3$, $\beta = 0.2$, $(\delta^1, \delta^2, \delta^3) = (0.15, 0.2, 0.1)$ and $(0.1, 0.15, 0.05)$, and $\eta = 0$ and 2.0. Figures 6 and 7 display the numbers of pedestrians selecting each exit when all pedestrians are randomly distributed in the whole space of the room and in the region IV at initial time of the simulation, respectively (see Fig. 1).

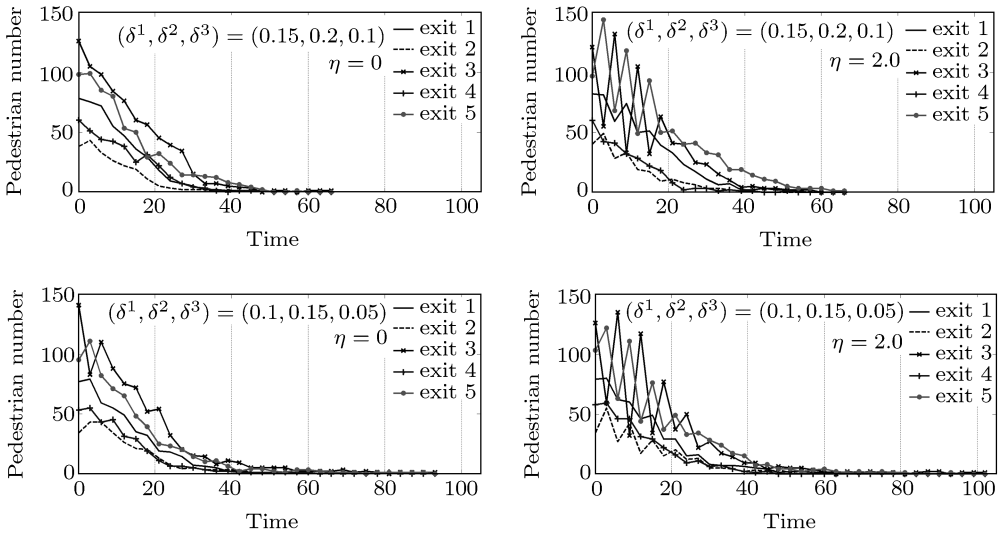


Fig. 6. Number of pedestrians selecting specific exits when all pedestrians are randomly distributed in the whole space of the room.

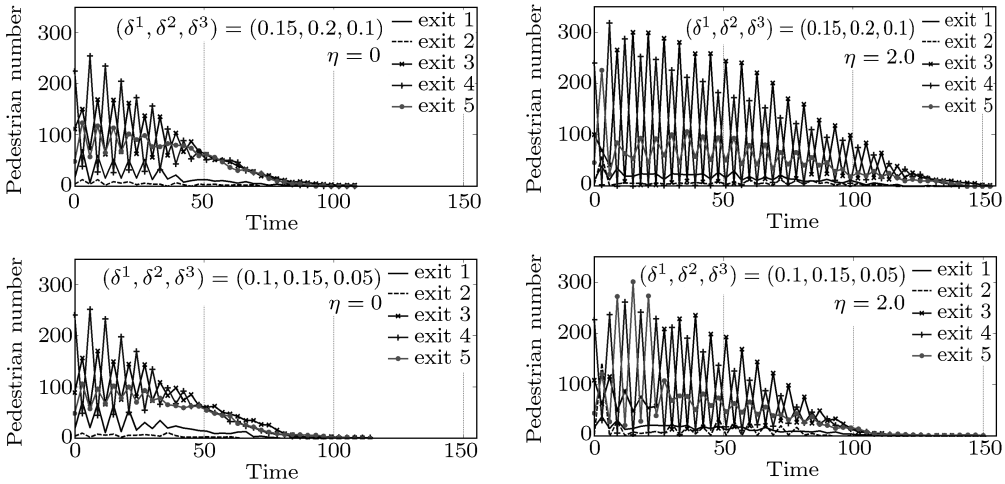


Fig. 7. Number of pedestrians selecting specific exits when all pedestrians are randomly distributed in region IV.

It can be seen from Fig. 6 that for each of the two groups of $(\delta^1, \delta^2, \delta^3)$, when the η-value increases from 0 to 2.0 (i.e, the emergency guide sign provides exit information according to not only the route distance to exits but also the number of pedestrians selecting each exit as well as the exit width), some pedestrians hesitate in exit choice and prefer to frequently change their target exits during evacuation. For a fixed η-value, the evacuation time increases when all elements in $(\delta^1, \delta^2, \delta^3)$ decrease. This is because pedestrians cannot be reasonably assigned to exits, congestion occurs near some exits while the other exits are rarely used.

In Fig. 7, when $\eta = 0$, the evolutionary process of the number of pedestrians selecting each exit is basically not affected by $(\delta^1, \delta^2, \delta^3)$. When $\eta = 2.0$, radical oscillation can be observed in the evolution. If all elements in $(\delta^1, \delta^2, \delta^3)$ are reduced by 0.05, the oscillation is weakened and the evacuation time can be saved correspondingly.

4. Conclusions

In this study, pedestrians are allowed to re-select their target exits in evacuation according to a nested logit discrete choice mechanism. This exit choice model is embedded in the cellular automata simulation implemented in Ref. [10] for simulating the evacuation in rooms with internal obstacles and multiple exits. A scenario of

evacuation is designed and tested. From the simulation results of this scenario, we find that (a) the evacuation time is determined by the degree of the pedestrian preference for each class of exits, besides the width of exits and the number of pedestrians selecting each exit; (b) in some cases, frequently re-selecting exits and well knowing too many exits may lead to higher evacuation time; (c) less considering the difference among exits may increase or decrease evacuation time, depending on the initial pedestrian distribution; and (d) the emergency guide sign can affect the evolutionary process of the number of pedestrians selecting each exit.

In future studies, the approach proposed in this paper will be used to design intelligent guide signs for improving the efficiency of evacuation.

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