Simulation study on pedestrian evacuation optimization in a multi-exit building

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Abstract. Two multi-exit selection models based on social force model are presented to simulate pedestrian evacuation, and the model coefficients are optimized by considering the effect of the exit distance, exit width, crowd number and distribution. The evacuation processes employing shortest distance evacuation strategy, static and dynamic exit selection model are compared. The effects of the crowd number, distribution and desired speed are investigated on the evacuation time and balance degree with the static and dynamic exit selection model. The effects of group size and group shape on the evacuation time in dynamic exit selection model is explored. The simulation results indicate that the proposed dynamic exit selection model can realistically reflect the pedestrian evacuation and help predicate the time available in building spaces with multiple exits, which can lead to a shorter evacuation time and higher evacuation efficiency. The study has some guiding significance for emergency evacuation and exits design of multi-exit buildings.

1. Introduction

The evacuation inside the building has the characteristics of gathering towards the safety exit and leaving the evacuation space through the competitive safety exit. How to realize fast and effective escape has become a research hotspot of building evacuation. Exit selection is one of the most important issues of simulation models. In the actual evacuation process, people often consciously or unconsciously face with the problem of exit selection, which is a complex thinking process in the evacuation process of pedestrians. Therefore, it is necessary to establish a corresponding mechanism for individual exit selection to simulate the evacuation process in multi-exit venues.

Social force model is a typical micro model, which represents various psychological factors, social factors and external environmental factors that affect evacuation, and can simulate the behavior characteristics and common evacuation phenomena of evacuation [1]. Some related researches about crowd evacuation and exit selection strategy have been done [2-8]. Lovreglio et al. [2] studied the conformity behavior of evacuees in exit selection by situation with a large number of evacuees gathered in front of an exit, ignoring other available exits. Xu et al. [3] used the cellular automata model to simulate the exit choosing behavior of evacuation crows under a multi-exit room based on surrounding pedestrian density. Wang et al. [4] combined cellular automata model with multi-agent model, studied the behavior characteristics of individuals in panic state, simulated the panic evacuation of individuals in a room with obstacles, and established the command evacuation model on
this basis to guide the safe evacuation of individuals. In above studies, the characteristics of dynamic exit changing for asymmetric crowd distribution and different exit conditions are not well represented.

Anylogic software have been used to crowd evacuation strategy [9-12]. Zhang et al. [10] developed a systematic simulation-based multi-attribute decision approach to route choice planning. Haris et al. [11] proposed a modeling framework incorporates Anylogic simulation environment to design complex spatial environment for large-scale pedestrians as agents, in order to provide the safest and nearest evacuation path because during disastrous situations there was possibility of exit gate blockade and directions of evacuees may have to be changed at run time. By the framework, run time diversions have been given to evacuees to ensure their quick and safest exit. Choi and Chi [12] developed a computational model using hazard prediction data to identify optimal evacuation routes, the safest and shortest paths to the nearest exit, during the event of a building fire. Based on this software platform, further model construction and optimization research need to be carried out for complex crowd simulation.

This paper presents two exit selection optimization models which take into account the distance, exit width, density of evacuees of the exits, and desired velocity. The main consideration is the realization of dynamic exit changing and model coefficient optimization.

2. Model formulation
The social force model can reflect the anisotropic character and dynamic features of pedestrian interaction, and thus, provides a basis for simulating the pedestrian evacuation process. Aiming to improve the effectiveness of the exit selection strategies during the pedestrian evacuation, a systematic simulation-based decision approach is developed to investigate on how to simulate, assess and improve the efficiency of the evacuation exit selection planning.

2.1. Social force model
The social force model [1] is one of the most popular models to simulate pedestrian movement, which is defined by the following motion equation.

\[
\frac{m_i \, dv_i}{dt} = m_i \, v_i^0(t) \, e_i^0(t) - v_i(t) + \sum_{j \neq i} f_{ij} + \sum_{w} f_{iw}
\]  

(1)

where \( m_i \) stands for the mass of pedestrian \( i \); \( v_i \) stands for the actual velocity; \( v_i^0 \) is the desired speed; \( e_i^0 \) is the unit vector pointing to the desired target; \( \tau \) is a certain characteristic time; \( f_{ij} \) and \( f_{iw} \) are the interaction force from other pedestrians and walls, respectively.

Pedestrians often walk together in evacuation, which has a significant impact on the congestion degree and evacuation efficiency. The attraction force between group members can be expressed in the following form [13].

\[
f_{iq} = -F_i \exp\left(\frac{r_{iq} - d_{iq}}{B_i}\right) n_{iq}
\]  

(2)

where \( r_{iq} \) represents the sum of radius of the pedestrians, \( d_{iq} \) is distance between pedestrians and \( q \) represents the friend of pedestrian \( i \), \( B_i \) and \( F_i \) are constant \( n_{iq} \) represent the unit vector from \( q \) to \( i \).

2.2. Static exit selection model
If the shortest distance model is used in a multi-exit building with exits of different widths or asymmetrical layout of pedestrians, the evacuation process will suffer imbalance, i.e. overcrowding will appear in front of the nearest exit to pedestrians while the far exit is not fully utilized. According to Ref. [14,15], the balance evacuation can be achieved by adjusting the sub-area belonging to an exit under the situation with an asymmetrical pedestrian and exit layout, but they did not consider the effect of desired velocity. In a real evacuation scene, there exists different categories of individuals.
with obvious different desired velocity, so changing individual evacuation routes by altering the evacuation time is an effective way. The evacuation time can be adjusted in a static model by employing exit weight coefficient according to the crowd distribution, exit condition and desired velocity, \( w_i \in [0,1] \), as shown in Eq. (3). Proper exit weight coefficients can redistribute exit selection reasonably, the crowds can evacuate from the building with shorter time.

\[
I_{\text{min}} = \min \left\{ \frac{w_id_m}{v_0}, \ldots, \frac{w_id_M}{v_0}, \ldots, \frac{w_md_M}{v_0} \right\} \tag{3}
\]

2.3. Dynamic exit selection model

In order to select one exit to move towards, the pedestrian need consider these factors, namely path distance, exit efficiency (the number of pedestrians and exit width). When path distance is the dominant factor, the probability of exit \( m (m = 1, 2, \ldots, M) \) to be selected is given by \( P_{d_m} \). The parameter \( d_{im} \) is the distance between the pedestrian \( i \) and the exit \( m \).

\[
P_{d_m} = \frac{\exp(-d_{im}/v_0)}{\sum_{i=1}^M \exp(-d_{im}/v_0)} \tag{4}
\]

When exit efficiency is considered, the probability of exit \( m \) to be selected is given by \( P_{r_m} \). \( r_m \) is assumed to denote exit efficiency, which is equal to the number of pedestrians who select exit \( m \) and their distance to exit \( m \) is nearer than pedestrian \( i \), divided by the maximum evacuation capability of exit \( m \), \( N_m/C_m \).

\[
P_{r_m} = \frac{\exp(-N_m/C_m)}{\sum_{i=1}^M \exp(-N_m/C_m)} \tag{5}
\]

Considering the compound factors of distance and congestion are more beneficial to evacuation. The probability \( U_{im} \) of selecting exit \( m \) is given in Eq. (6), which is calculated once per second.

\[
U_{im} = \alpha P_{d_m} + (1 - \alpha)P_{r_m} \tag{6}
\]

\[
\max(U_{1i}, U_{2i}, \ldots, U_{Mi}) - U_{it} > \text{dU} \tag{7}
\]

where \( \alpha \) is a weight parameter representing the relative importance of path distance and exit efficiency. \( U_t \) and \( \max(U_{1i}, \ldots, U_{Mi}) \) denote the probability of target exit and maximum probability of other exits respectively. If the maximum probability of other exits is greater than the probability of pedestrian’s original target exit and the difference exceeds the threshold \( \text{dU} \), then pedestrian will change the target exit and choose the target exit with the maximum probability. Otherwise, pedestrian will keep the original target exit.

2.4. Simulation procedure

The model is built using the AnyLogic simulation software, which provides a user friendly simulation environment, allows the modelers to quickly create and simulate high fidelity models of complex systems. It supports different modelling techniques such as discrete event, multi-agent, system dynamics and hybrid system. Anylogic provides rapid prototyping through a user-friendly interface, Java-based development environment and a set of multipurpose component libraries, which help to speed up the modelling process for pedestrian motion simulation [13-14].

The coefficient optimization can be conducted by OptQuest optimizer of Anylogic [16]. For static exit selection model, the OptQuest optimizer environment in the Anylogic is defined as follows: The objective function maximize the root.maxTime. The maximum number of iterations for optimizing system simulations is set to 1000. The constraint condition is \( w_i \in [0,1] \).

For dynamic exit selection model, the threshold \( \text{dU} \) can reflect pedestrian’s urgency of changing the target exit, and the weight coefficient \( \alpha \) reflects the importance of path distance. Pedestrians will
only consider the distance factor and choose the closest exit for \( \alpha = 1 \), the evacuation model without considering the density around the exit. For \( dU = 0 \), if \( \alpha > 0.5 \), there is no exit selection change; if \( \alpha < 0.3 \), the change is too frequent, the density around the exit is the important factor affecting exit selection, and much time is spent on the route to the exit. For \( \alpha \in [0.3, 0.5] \), if \( dU > 0.3 \), almost nobody change target exit. That is because when \( dU \) is too large, it is difficult for pedestrians to change the target exit even though the situation of other exits is much better than the current target exit. Under these circumstances, congestion may occur around target exit, which makes the utilization of exits unbalanced. Under the constraint conditions of \( \alpha \in [0.3, 0.5] \) and \( dU \in [0, 0.3] \) in optimization experiment, the optimal evacuation time is found when \( \alpha = 0.45 \), \( dU = 0.05 \), which are adopted in the following simulation.

The flowchart of static and dynamic exit selection model for evacuation environment is shown in figure 1 and figure 2.

For dynamic exit selection model, though pedestrians meet the requirement of replacing exits, they have the probability to maintain the preceding exit, and pedestrians usually change exits no more than three times. These can prevent pedestrians from changing the target exit frequently. The main simulation procedure for dynamic model follow these steps.

1. First, initialize the building environment, set the desired speed and diameter of pedestrians, and distribute pedestrians in the building space. Then start the evacuation process.
2. Flowing, calculate the shortest distance of each exit, calculate the number of pedestrian who chooses the exits with shorter distance to the exit. Then, the optimized exit selection strategy is started. Through calculating \( P_{dim} \) and \( P_{nim} \) for pedestrian \( i \), max(\( U_i \), \( U_m \)) are updated every second. Pedestrians initially select the target exit with the maximum probability. If the difference between max(\( U_i \), \( U_m \)) and the current target exit probability \( U_i \) is above a certain value and the total changing times for each person is less than three times, the target exit will be altered to the exit with the maximum probability. Otherwise, the original exit remains unchanged. Then at the next second update calculation, until all pedestrians are evacuated.

![Figure 1. Flowchart of static exit selection model.](image1)

![Figure 2. Flowchart of dynamic exit selection model.](image2)

3. Results and analysis

In emergency, pedestrians usually have multiple modes of evacuation affected by physical environment psychological factor. Therefore, it is very necessary to understand the exit selection mechanism by analyzing the static and dynamic exit selection conditions and evacuation performance. Besides, an important characteristic of evacuation is the evacuation time which is an essential property in the representation of human survivability in evacuation models.

In order to verify the availability of the above models, a series of cases are designed to realize evacuation simulation of a multi-exit building. The size of a building space is 45*25 m. There are four
exits in the middle of four sidewalls with the widths of 1.0 m, 1.5 m, 2.5 m, and 3.5 m, respectively. Two kinds of distribution of pedestrians are designed, as shown in figure 3. The distribution of pedestrians is random and uniform in two areas. The diameter of pedestrian is 0.4-0.5 m, and the desired speed is among 0.5-1.5 m/s.

![Diagram of exit positions and initial distribution of pedestrians.](image)

3.1. Applicability analysis of the two models

In this part, three scenarios are designed: scenario 1 (dispersed distribution with desired speed of 1.0-1.3 m/s), scenario 2 (concentrated distribution with desired speed of 1.0-1.3 m/s), and scenario 3 (dispersed distribution with desired speed of 0.5-1.5 m/s).

Figure 4 shows the pedestrian evacuation process with different strategies for pedestrians (N=600) randomly distributed in the building space. Figure 5 shows the evacuation time and number of evacuated pedestrian at each exit. When selecting the exit using the shortest distance strategy, pedestrians tend to gather to the nearest exit and waste other evacuation exit, as shown figure 4(a). In the later time stages, people just use exit1 and exit2. For static model, more people choose the exit4. The utilization rate of the exits is increased and evacuation time decreases. Comparing the evacuation process, according to the dynamic model, the utilization rate of the exits better than that with static model, and the motion efficiency is slightly higher. This is due to the fact that under the dynamic model, the exit distance, the number of pedestrians and the crowd density are dynamically taken into account comprehensively, which can effectively avoid the imbalance phenomenon of exit and improve evacuation efficiency. As time increases, based on the effectiveness of the dynamic exit selection strategy, as shown in figure 4 (c), some pedestrian give up the nearest exit, and choose the exit close to the relatively wide and loose exit, which is the same with the real scene of sparsely scattered field.
As shown in tables 1 and 2, the values of exit weight coefficients are affected by both crowd density and distribution for the static model with varying optimization results $w_k$. The coefficients ($α=0.45, dU=0.05$) for the dynamic model remain unchanged and it shows better performance in both the evacuation time and exit balance. The static model can reduce the whole evacuation time, but the exits are not fully utilized, especially for cases with concentrated distribution.

3.2. The effect of group size, and group shape on evacuation
In the process of evacuation, pedestrians would form groups of different sizes and forms. Using dynamic exit selection model strategy, cases is conducted for 600 pedestrians with varying group percent (0%, 25%, 50%, 75%, 100%) and group size (2-3, 4-5, 6-7), randomly distributed in the building space and desired velocity to be 0.7-1.3 m/s. As shown in figure 6, with the increment of group size, the evacuation time increases for higher group percentage. That is because for large group size and group population using dynamic model changing exit strategy it is easy to cause collision countercurrent.

Furthermore, during pedestrian movement, the pedestrian group can keep certain shape, including swarm, front and chain, as shown in figure 7 and figure 8. Figure 9 indicates that the evacuation time is obviously less with the chain shape. The evacuation time with swarm shape is slight better than that with front shape.

4. Conclusion
In this paper, we have proposed two exit selection models based on social force model for pedestrian evacuation. The model coefficients can be achieved through OptQuest optimizer of Anylogic.

For uneven distribution of crowds and different exit conditions, the dynamic exit selection model can effectively balance the evacuees between different exits and maximize the evacuation efficiency by fully considering the density in the exit area, desired velocity, exit distance and width. By comparison, the static exit selection model have a good performance on the whole evacuation time, but the exit balance is not very well especially for asymmetric distribution of crowds. Moreover, with the increment of group size, the evacuation time increases for higher group percentage, and the evacuation time is obviously less with the chain shape in dynamic exit selection mode.

Through the simulation analysis, the two models can reappear and explain the evacuation situation of multi-exits in the real world. Meanwhile, it can be used as a reference for the simulation research of pedestrian evacuation and building exits safety design.
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