DEVELOPMENT OF A SIMULATION MODEL FOR PEDESTRIAN EVACUATION UNDER FIRE CONDITION

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ABSTRACT

Understanding pedestrian behavior under emergency conditions is critical for emergency preparedness. However, the high cost associated with field experiments limited the opportunities for exploring large-scale pedestrian behavior under various emergency scenarios. As an alternative, pedestrian modeling and simulation has become increasingly important in emergency studies. An efficient and valid simulation model that can facilitate the analyses and tests of different emergency management plans is still needed. Thus, this study aims to develop an improved simulation model for analyzing pedestrian movement under fire evacuation. The proposed model was built upon conventional social force model but with extended module addressing pedestrian behavior changes. The model was incorporated in simulation under Unity context and verified from different aspects. The proposed model was then applied to a fire evacuation experiment. Comparative experiments were conducted and the simulation results suggest that the proposed model is more appropriate for simulating pedestrian behavior under fire evacuation.

Keywords: pedestrian evacuation, simulation, fire safety, Unity, simulated annealing.

1 INTRODUCTION

Fire risk is one of the most critical concerns about the safety of residential buildings, public, and business facilities. Many historical fire incidents occurred in public areas were reported to have unsuccessful pedestrian evacuation plans that consequently led to catastrophic results. For example, the Daegu subway fire in Korea, 2003 resulted in 192 causalities (Hong 2004) and Kitzseinhorn funicular fire in Austria, 2000 claimed the lives of 155 people (Schupfer 2001). To mitigate the risk of getting more pedestrians trapped under fire conditions, emergency preparedness becomes very important. One of the key tasks prior to the development of well-planned and organized evacuation programs is to understand human movement behavior in emergency circumstances. However, it is impractical and unethical to expose pedestrians in real fire experiments to study their evacuation behavior.

Alternatively, many fire evacuation simulation models have been proposed in recent years to analyze pedestrian behavior under emergency situations. For example, an early simulation model, namely

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EXODUS, was used to predict pedestrian behavior under aircraft fire circumstances (Alizadeh 2011). Later, important factors, such as 'waiting time' for evacuation under crowded areas, were considered in the models for simulating evacuation in malls and public areas (Chow and Ng 2008). With the development of simulation models, actual fire events such as the Rhode Island Nightclub fire were simulated and analyzed in many studies such as Galea *et al.* (2008) and Grosshandler *et al.* (2005). However, it should be noted that both local and global optimum decisions of pedestrians during fire evacuation were seldom considered in these existing studies.

With various fire evacuation simulation models, the design and construction of new facilities and fire legislation also benefit from the simulation results. For example, a numerical simulation tool, namely FDS+Evac, that combines fire model and evacuation model had been widely used in fire evacuation (Korhonen *et al.* 2010). It was also frequently used to analyze the construction of new facilities with special considerations of fire evacuation (De-Ching *et al.* 2011). Ronchi *et al.* (2013) had reviewed and compared several evacuation models (e.g., FDS+Evac, Steps, and Simulex) when analyzing the applicability of the Italian Fire legislation for tunnel safety. Despite great efforts, these studies still did not sufficiently consider a number of fire evacuation issues associated with evacuation flow characteristics, data deficiency, accurate physical interactions, etc. (Larusdottir and Dederichs 2011).

This study aims to develop a simulation model for analyzing pedestrian evacuation under fire condition. The proposed model extended the conventional social force model to capture complex pedestrian behavior under emergency conditions and was incorporated in simulation in the context of Unity. Unity provides powerful game engines and fully integrated professional toolkits. Specifically, it offers numerous well-established components that leverage the modeling and visualization of various physical interactions and environments (Chiu and Shiau 2016). By taking advantages of the Unity, we intend to offer users a simple but valid simulation model for assessing different evacuation strategies and programs, facility designs, etc.

The remained parts of this paper are organized as follows. Section two provides a comprehensive literature review. Section three describes the proposed models. Section four illustrates the development of the simulator. Section five presents the validation study. This is followed by the results and discussion of experimental tests. Finally, the last Section concludes the study.

2 LITERATURE REVIEW

Fire evacuation is a complex process that often involves many pedestrians. A number of studies have been focused on the development of suitable models to simulate the complex interactions among pedestrians under fire evacuation conditions. In general, the majority of the existing studies can be grouped into three categories: cellular automaton (CA) models, agent-based models, and social force models.

In general, CA models divide the evacuation space into a set of cells that can be occupied by different pedestrians with certain transition rules. For example, basic CA model was introduced by Blue and Adler (Blue and Adler 1998) to study pedestrian movement while only adjacent and empty cells could be targeted by a pedestrian along the walking path. Numerous extensions and applications of the basic CA model have been developed in recent years. Kirchner *et al.* proposed a bionic-inspired CA model to simulate the herding behavior (Kirchner and Schadschneider 2002), and further considered using the stochastic CA model (Kirchner *et al.* 2004) to address the friction affection and clogging. However, due to the flexibility of pedestrians in the cell and the corresponding transition rules, CA cannot well depict detailed characteristics of pedestrians during fire evacuation.

Rather than focusing on the space area, the agent-based models concern more about pedestrians and treat each pedestrian as an agent with different goals, rules and optimization methods. It can model the heterogeneity of different pedestrians with different sets of rules that govern the movement of each agent. For example, Pan *et al.* (2007) proposed an agent-based model that can demonstrate some complex emergent behaviors such as competition, queuing, and herding behaviors. Izquierdo *et al.* (2009) applied the particle swarm optimization (PSO) to assess the behavioral patterns and the evacuation time. Despite the improvement, the complexity of multi-agent based models will increase dramatically given the growing combinations of destinations and goals of different pedestrians. Thus, these models cannot be easily scaled.

The social force models calculate the evacuation routes of pedestrians by introducing the social force equations for crowd dynamics. The computational complexity of social force models is more acceptable than that of the multi-agent based models. In addition, it can well describe human characteristics. Helbing and Molnar (1995) proposed the model to emulate pedestrian actions under normal conditions and it can be enhanced by introducing various features or variables to mimic pedestrian behavior in emergency evacuation. Examples of the forces include: (a) the acceleration to maintain desired movement speed; (b) the attractiveness to final destination; and (c) the tendency to maintain certain distance between other pedestrians and obstacles. For example, Xu and Huang (2012) considered pedestrian's direction visual field to refine the social force model during emergency evacuation. In most of the existing studies, the probability that pedestrians can jump out of the local optimum to choose another evacuation route was not considered during simulation.

Regarding the typical issues associated with the existing methods for pedestrian evacuation simulation, the present paper introduces an improved social force model that incorporates simulated annealing (SA) to simulate pedestrian movement under fire evacuation scenarios.

3 METHODOLOGY

The improved social force model calculates the social force of each pedestrian and determines their moving directions and speeds accordingly. Then, it adapts the SA scheme to provide the pedestrian the ability to select another direction and speed to jump out of the local optimum. The detailed description of model is presented below.

3.1 Social force model

Social force model uses the socio-psychological and physical forces to simulate the movement of pedestrians. Each pedestrian is driven by force vectors. Usually, it consists of three types of forces under fire conditions:

$$\begin{aligned} f &= f_{neigh} + f_{wall} + f_{fire} \\ f_{neigh} &= A_i e^{-\frac{d_{ij}-r_{ij}}{B_i}} \left(\lambda_i + (1-\lambda_i)\frac{1+\cos\varphi_{ij}}{2}\right) n_{ij} \end{aligned} \tag{1}$$

where d_{ij} denotes the distance from the i^{th} pedestrian to the j^{th} pedestrian; r_{ij} denotes the sum of the radius of the i^{th} pedestrian and the j^{th} pedestrian; φ_{ij} is the angle between current speed direction and the vector formed by the positions of i^{th} pedestrian and j^{th} pedestrian; n_{ij} is the normalized vector between the positions of i^{th} pedestrian and j^{th} pedestrian; λ_i represents the parameter to measure the angle effect; A_i and B_i are the parameters used to tune the extent of the influence of the distance; and f_{wall} and f_{fire} can be computed using the same equation as f_{neigh} but different parameter values.

Pedestrians are likely to have a limited view during fire evacuation. Thus, only neighbors in certain range are considered to be the valid neighbors of i^{th} pedestrian to generate the social force. Equation (2) is used to determine the neighbors where ε is the threshold to determine the neighborhood membership function.

$$\text{if } d_{ij} < \varepsilon, i \in Neighbor(j); else\ i \notin Neighbor(j) \tag{2}$$

In this study, the choice of pedestrian model is based on the model in Korhonen *et al.* (2010). Figure 1 shows the hypothesized pedestrian dimension in simulation.

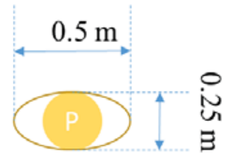

Figure 1: Model for pedestrians.

3.2 SA scheme

The social force model calculates the force and then determines the speed and direction of a pedestrian accordingly. However, the objective function for computing the force on the spatial and temporal dimensions is not convex and thus can have many local optima. For example, one exit might be very crowded while the other one is less used. Thus, it is necessary to enable pedestrians to jump out of the local optimum evacuation directions to achieve a shorter evacuation time.

This study proposes to use the SA approach to achieve the goal of adjusting pedestrian behavior if trapped in local optima. SA is a probabilistic technique for approximating the global optimum of a given function (Hwang 1988). Specifically, it is a metaheuristic approach to approximate global optimization in a large search space. It is often used when the search space is discrete (e.g., all tours that visit a given set of cities).

In the simulation scenario, the route selection of a pedestrian will be dominated by the calculated social force. However, each pedestrian still has the opportunity to quit from the current selection while choosing another route that lead to another exit with less number of pedestrians. The search space of the optimization problem is discrete for there only exist several exits, thus SA with a smaller computational complexity compared with other intelligent algorithms like Bayesian belief network (BBN), ant colony algorithm (ACO) is more acceptable. It also should be noticed that the temperature of SA will degrade and thus the acceptable probability will be smaller during the iteration. Then, the chance that pedestrians change their exits will decrease during the simulation process. This is in accordance with the realistic pedestrian psychology for pedestrians will tend not to change their decisions after a long time and the accordingly sunk cost. Thus, the SA scheme is applied to enable pedestrian to jump out of current route.

Each pedestrian will calculate his social force to the current exit and other available exits. If the smallest social force value of other available exits is small than that of current exit, the pedestrian will turn to the new exit. Otherwise, the pedestrian will have an acceptable probability to decide whether or not to change the exit. Pseudo code in Table 1 is used to implement the SA approach for adjusting the route of a pedestrian and the new speed and force will be updated given a new movement direction of the pedestrian.

Table 1: Pseudo code for the SA scheme.

Input: M walls, N pedestrians, H fires, K exits
Initialization: identify neighbors for each pedestrian, starting temperature T_0, and annealing parameter C
Iteration $r = 1$;
While $(N > 0)$ **do:**
    $r = r + 1$
    for each pedestrian **do:**
        select the nearest exit
        for each neighbor, wall, fire **do:**
          calculate social force *f*: $f = \sum_{i=1} f_{negh} + \sum_{j=1} f_{wall} + \sum_{q=1} f_{fire}$
        end for
        update current temperature

$$T(C,r) = T_0\text{-}C \times (r\text{-}1)$$

calculate social force f_{new} for other K-1 exits
select the minimum f_{new} and accordingly exit
if $f_{new} \leq f$
  choose the selected exit & **update** social force f
else
  calculate the acceptance probability

$$P(T, f, f_{new}) = e^{\frac{f - f_{new}}{T}}$$

  if P(T, f, f_{new})>random(0,1) **do:**
    choose the selected exit & **update** social force f
  end if
end if
end for
  if *a pedestrian successfully evacuated* **do:**
    N=N-1
  end if
end while

4 SIMULATOR DEVELOPMENT

As shown in Figure 2, the schematic of the simulation model is implemented in Unity. The ***GameController.cs*** file in Unity is used for building the fire evacuation environment and configuring parameters such as the number of pedestrians and fire sources. Each pedestrian is represented by a yellow model shown in Figure 3. When the "Generate" button is pressed, initial distributions of pedestrians, walls, exits, and fires are generated. When the "Evacuate" button is pressed, the ***PeopleBehavior.cs*** file is called for implementing the SA-based social force model and accordingly updating the pedestrian's position and speed. When all pedestrians are evacuated, the trajectories can be archived in a text file for further analysis.

The snapshot of the simulator is illustrated in Figure 3: (a) and (b). The scenario is a corridor with the width of 4 m and the length of 20 m. The two green boxes at the two end represent the exit while the red flame depicts the fire source. Pedestrians will update their positions and speeds during the evacuation process. The total evacuation time is monitored. The four purple rectangles represent the area A, B, C, and D and the number of pedestrians in each area is counted and shown below the total evacuation time. For tracing a pedestrian, users just need to click the specific pedestrian of their interest. The pedestrian selected will be highlighted in pink and the simulation process will be paused. Key information such as ID, position, speed, and area currently being occupied is displayed and the "Resume" button is used to continue the simulation process, if necessary. The save and print buttons will only present when all pedestrians successfully evacuate from the simulated scenario.

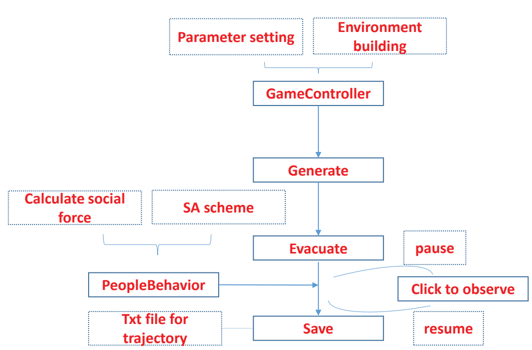

Figure 2: Schematic of the simulation model.

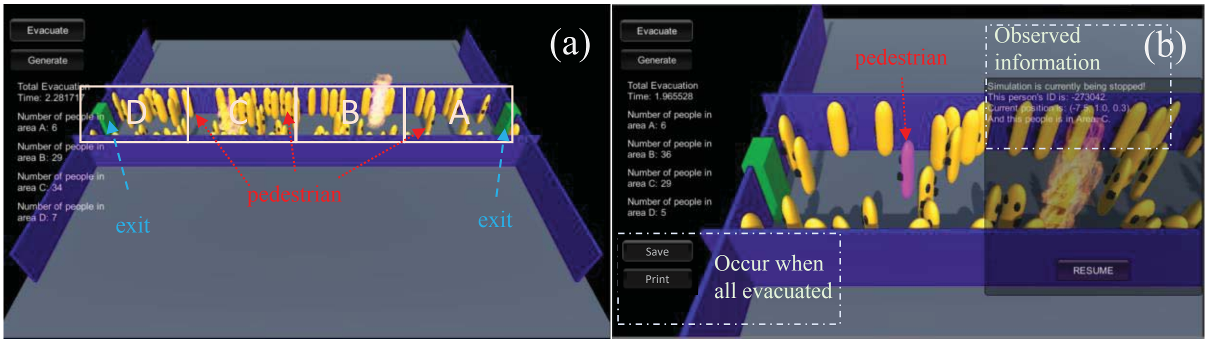

Figure 3: Simulation model development in Unity: (a) simulation design; (b) function demos.

5 SIMULATION VALIDATION

The improved social force model simulates pedestrian movement under emergency evacuation. Model validation is important so that the develop model can well represent real traffic phenomena being examined. In the present paper, the validation process is conducted by analyzing the speed-density relationship, flow-density relationship, and comparing the total evacuation time with the theoretical evacuation time.

5.1 Fundamental diagram

Fundamental diagram is an important tool in transportation engineering for analyzing the relationship between traffic speed, flow, and density. We have designed a test scenario as shown in Figure 4 to examine the fundamental diagram of the simulated pedestrian movement under normal condition. The arrival of pedestrian was assumed to follow Poisson distribution. Pedestrians were assumed to have an expected speed of 1 m/s.

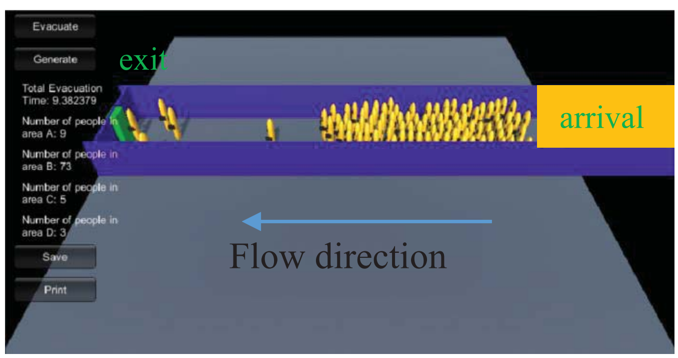

Figure 4: Simulation scenario for fundamental diagram.

Figure 5 shows the fundamental diagram. The relationship between density and speed is shown in Figure 5 (a). Each dot in the scatter plots represents a sample measurement by integrating the collected trajectories of pedestrians with an interval of 5 seconds. When the density increases to 4 peds/m^2, the speed reduces to about 0.6 m/s, which reflect a highly congested scenario. When the density is less than 2 peds/m^2, the speed is almost at the free flow speed of 1 m/s. Overall, the average pedestrian speed tends to decrease as the density increases. Likewise, the flow-density relationship is depicted in Figure 5 (b). With the increase in density from a low value, the flow of pedestrian increases and then decreases with a rapid speed due to the congestion.

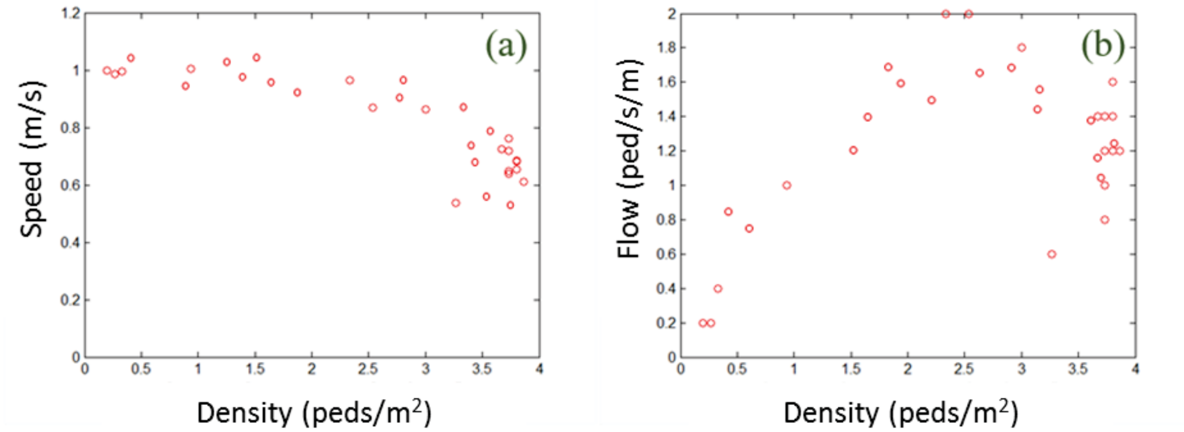

Figure 5: Fundamental diagram: (a) density-speed; (b) density-flow.

Compared with the observed pedestrian traffic flow in confined passageways with the width of 7.07 meters and the length of 7.20 meters (Chen *et al.* 2010), the level passageway has the starting speed of 1.3m/s. The peak of the flow appears at the density of 2 peds/m^2 with the value of 70 peds/min/m. Our flow appears at the density of 2 peds/m^2 achieve the flow of 1.4 peds/min/m (84 peds/min/m). The simulated results in this study achieved the maximum flow of 2 peds/s/m (120 peds/min/m) at the density of 2.5 peds/m^2. Though not perfect match field observations, the main trend of the fundamental diagram based our simulation is comparable to the empirical observations associated with real passageways in literature.

5.2 Evacuation time

Other than verifying the fundamental diagram, this study also examined the evacuation time obtained through our simulation model and compared it with the theoretically modeled ones. Evacuation time is approximately a monotonically increasing linear function to the number of occupants when the number of occupants is more than a threshold. The theoretical evacuation time model proposed by Togawa (1955) has been widely applied. The calculation method of moving time varies based on evacuation channels. However, the exit is often crowded with panicking pedestrian, making it more difficult to calculate the realistic moving time. The current model shown in (3) is an empirical equation based on field observations.

$$T = \frac{P}{Nd} + \frac{L}{v} \tag{3}$$

where T is the escaping time (s), P denotes total number of pedestrian, N represents the flow at the exit (peds/s/m), d is the width of the exit (m), L depicts the shortest distance from the 1st evacuated person to exit (m), and v describes the evacuation speed (m/s).

For verification, we have set the exit width to be 1 meter and thus d should be 2*1=2 meters for two exits. The mean flow rate N is assumed to be 2 peds/s/m, and the evacuation speed v is set to be 1m/s. Considering the shortest distance L to be 1 meter, the total theoretical evacuation time of P=200 pedestrians is 200/2/2+1/1=51s. Meanwhile, the simulation time is about 56 seconds given all 200 pedestrians were evacuated. A more detailed comparsion between the theoretical evacuation time and the simulated evacuation time is shown in Table 2. The difference between the theoretical evacuation time and the simulated evacuation time with few people is large. This may be attributed to the influence of fire and the randomly distributed pedestrians over the spaceshown in Figure 6. When the number of pedestrains is increased (e.g., 170 and 200), pedestrains are genereated in a relativly crowded condition and the evacuation behavior of pedestrains will vary due to the congested situation. However, it is reasonable that the mean value of total evacuation time is closer to that of the therotic value compared with the mean value of pedestrains with a small number. This is due to that the impacts of fires and sparse distribution of pedestrians are alleiviated.

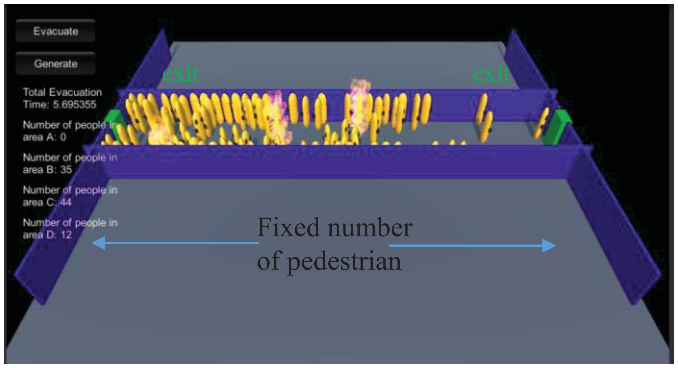

Figure 6: Simulation scenario for evacuation time.

Table 2: Theoretical evacuation time vs. simulated evacuation time.

# Pedestrians	50	80	110	140	170	200
Theoretical time	13.5	21	28.5	36	43.5	51
Simulated time	25.4±4.037	34.6±3.718	41.8±3.681	45.6±3.577	49.8±4.577	56.2±4.805

6 EXPERIMENTAL TEST

An experimental test is performed with three simulated fire sources and 100 pedestrians in a corridor with the width of 4m and the length of 20m. As shown in Figure 7, pedestrians generated near the left exit is dense while pedestrians generated near the right exit is sparse. All three fires locate at the closer to the left exit of the corridor. The expected speed of all pedestrians is set to be 1m/s. The choice of key parameters such as A_i and B_i that may affect the final output is chosen after a number of pilot tests and based on the reference values in Korhonen *et al.* (2010). The final social force parameters of the pedestrian-pedestrian interaction in this study are A =2000N, B=0.04m, and λ=0.5. The social force parameters of the pedestrian-wall interaction are A =2000N, B=0.08m, and λ=0.2. The fire impact parameters are A =4000N, B=0.1m, and λ=0.8.

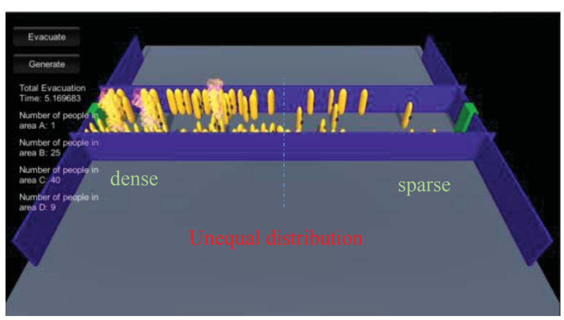

Figure 7: Snapshot of simulation model based on Unity.

As shown in Figure 8, the four subfigures (a), (b), (c), and (d) represent the simulated number of pedestrians in each small cell (0.5m×0.5m) at time t =1, 6, 10, and 35 seconds, respectively. These subfigures show that pedestrians tend to avoid the fire and evacuate more efficiently when the initial distribution of pedestrian is unequal over the space. As shown in Figure 8 (c), many pedestrians selected the right exit when the path to the left exit was congested and full of fire sources. Towards the end of simulation, the number of pedestrians near two exits both decreased to a small value as shown in Figure 8 (d).

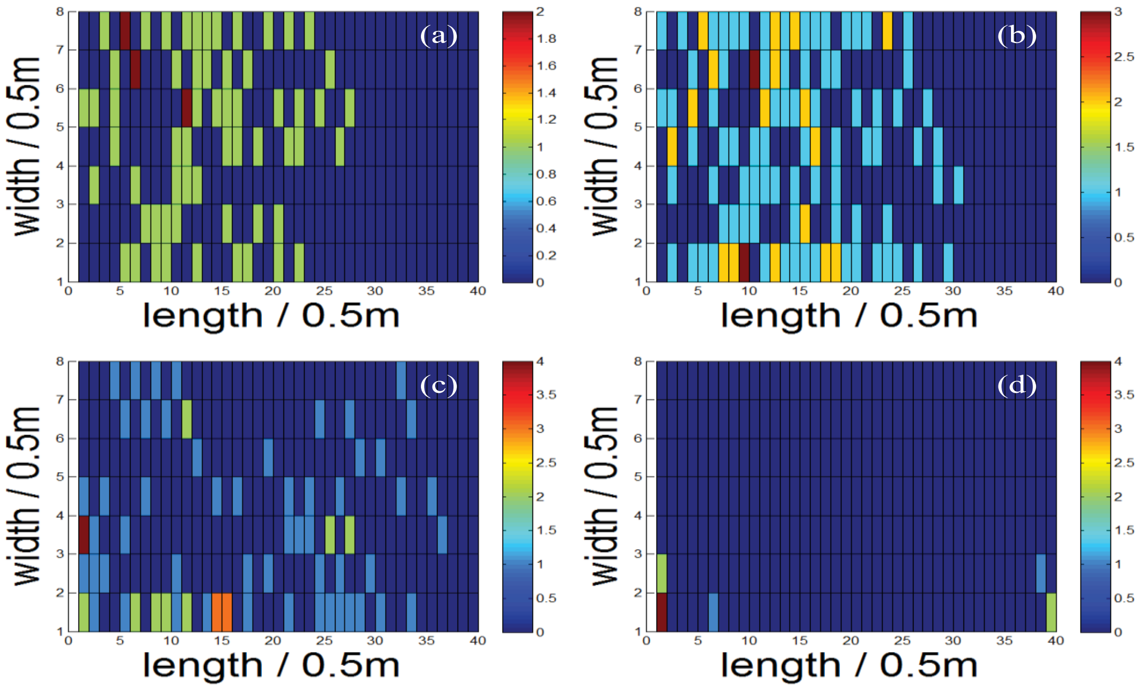

Figure 8 : Heatmaps of pedestrian distributions during fire evacuation with SA scheme.

For comparison, the simulation results without implementing the SA scheme are shown in Figure 9. The distributions of fires and pedestrians were the same as the aforementioned SA-based scenario. Pedestrians still avoided walking close to the fires but few of them can find successfully change their routes to the right exit that had fewer pedestrians and less fire impact. Thus, SA scheme can alleviate the impact of the initial pedestrian and fire distributions in the fire evacuation simulation.

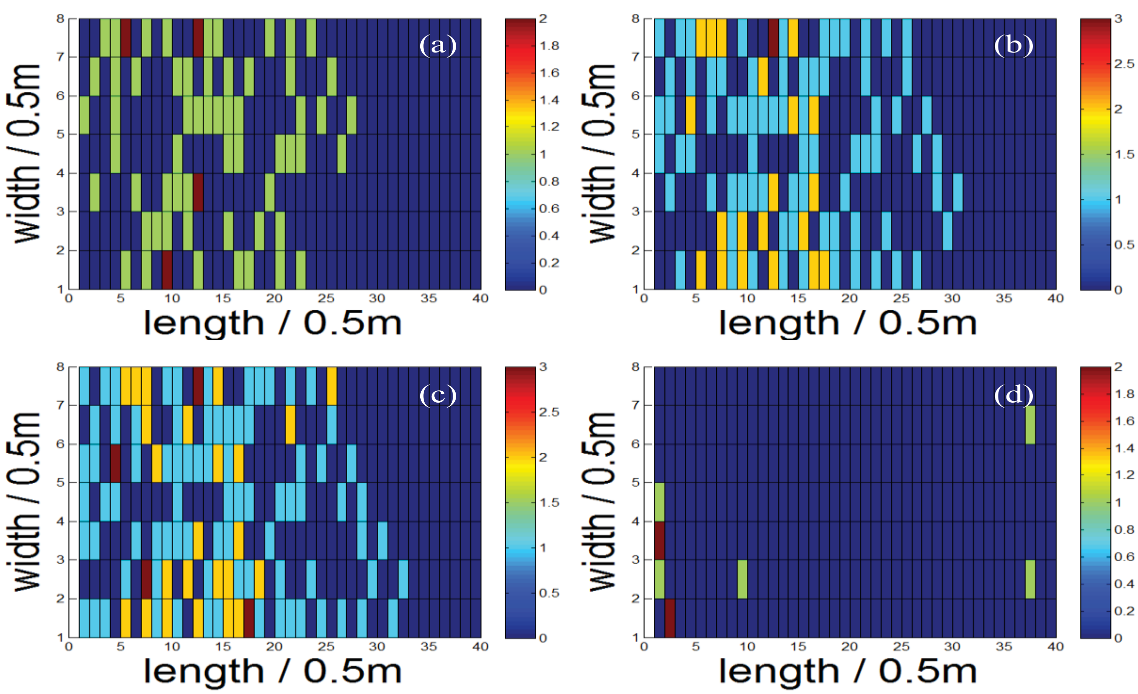

Figure 9: Heatmaps of pedestrian distributions during fire evacuation without SA scheme.

As a detailed example, Figure 10 illustrated the behavior change of a pedestrian when SA scheme was used. The pedestrian with ID 387906 changed his direction twice during the simulation. The previous direction and current direction with arrows in Figure 10 (a) depict that the pedestrian chose to change the moving direction when finding the left exit is acceptable after calculating the acceptable probability and comparing it with the random number. Later, due to observation that the number of pedestrians initially distributed near the right exit is less, the pedestrian finally selects to approach the right exit for evacuation for the social force value towards the right exit is smaller. Thus local optimum value can be adjusted by implementing SA scheme for considering other possible routes.

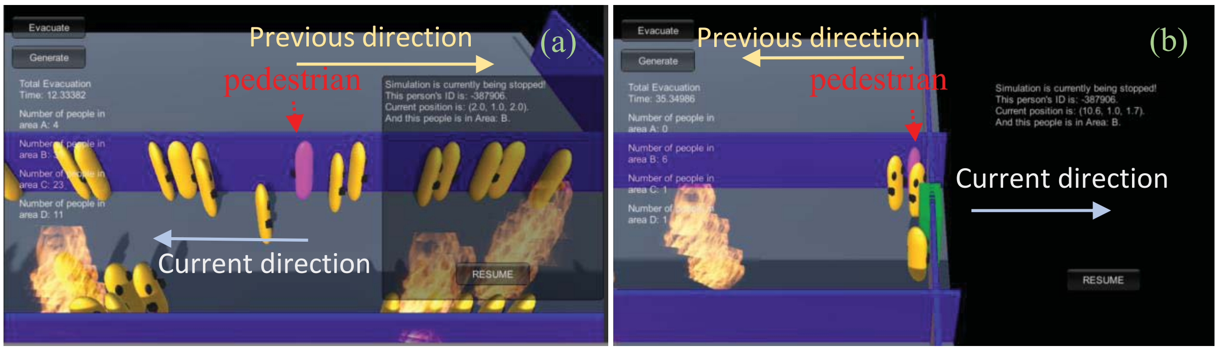

Figure 10: Pedestrian adjusted evacuation routes based on SA scheme.

7 CONCLUSION

Pedestrian modeling and simulation is important for emergency preparedness. This paper developed an improved social force model that incorporated simulated annealing mechanism in the context of Unity for simulating pedestrian behavior under fire evacuation. The validity of the proposed model has been verified with the fundamental diagram and evacuation time comparisons. The experimental test suggests that the use of the SA scheme can enable pedestrians modifying their evacuation decisions on route choices. This helps avoid the selection of local optimum route. Integrating the SA scheme with the social force model can alleviate the impact of initial distributions of pedestrians and fire sources on simulation results and obtain a more appropriate simulated evacuation time. The developed proposed simulation model on Unity is efficient and valid, and thus can facilitate the analyses and tests of different emergency management plans.

It should be mentioned that the developed model was not tested by using the data from real evacuation events. For practical implementation, more efforts on simulation calibration and validation based on field data are suggested and factors like panic in emergence fire evacuation, smoking influence and accordingly visibility should be taken into consideration. The sensitivity of the proposed model in response to different parameter configurations needs to be further examined.

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