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A model for simulation of crowd behaviour in the evacuation from a smoke-filled compartment

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ABSTRACT

The modelling of crowd evacuation from a building has been studied over the past decades. In this study, a numerical model based on cellular automaton is proposed to simulate the human behaviour termed "flow with the stream" in emergency evacuation from a large smoke-filled compartment. In the model, the smoke effect in the context of visibility is considered since visibility range can affect the human behaviour significantly. To simulate the reality that the smoke concentration in a fire compartment is not constant, the proposed model is developed to deal with the scenario in which the visibility range varies in the course of time. An empirical formula is incorporated into the proposed model to estimate the visibility range. The results of numerical tests show that the proposed model can also be used to investigate the effect of the number of guiders through case study.

1. Introduction

Fire incident in a building always threatens human life. Hence, evacuation of the occupants from the hazardous areas becomes an important issue. In the past decades, quite a number of approaches have been developed for the modelling of evacuation, among which cellular automaton (CA) is widely used [1–4].

Briefly, CA is a discrete dynamic consisting of a regular grid of cells, each in one of a finite number of states. In a CA model, time is also divided into many intervals, and the current state of a specific cell is determined by the states of its neighbouring cells at the last time step. CA was first proposed by Neumann [5] in the study of biological reproduction and crystal growth. Since then, it has been successfully applied in various areas, such as theoretical biology [6], fluid dynamics [7], traffic flow [8–11], pedestrian dynamics [12] etc. When CA is used in evacuation simulation, the space is normally discretized into uniform grid.

Obviously, the interaction among evacuees will affect the evacuation significantly. Recently, the modelling of human behaviour has become an important issue. For instance, Fang et al. [13] proposed a CA model based on simple human judgement to simulate bi-directional pedestrian movement and investigate the effects of back stepping and system size on the critical density of phase transition. Weng et al. [14] studied the dynamic characteristics of counter flow with different walking velocities and boundary conditions. Yang et al. [15] applied a two-dimensional model to the simulation of evacuation with respect to kin behaviour. However, it is very difficult for CA models to show all the aspects of human characteristics since human behaviour is extremely complicated. On the other hand, it is possible to use CA to study some particular issues. For example, Yuan and Tan proposed a basic model to consider three kinds of psychological behaviour, including group, unadventurous and inertia effects [16].

In a compartment with a fire origin, smoke affects the evacuation in two ways. First, smoke is harmful to evacuees' health. It is reported that inhalation injury from smoke and the noxious products of combustion in fires may account for

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about 60%–80% of fire-related deaths [17,18]. Second, the visibility range in the compartment may be reduced by smoke soot. In a space with low visibility, the behaviour of evacuees may be different from that in a normal environment. For example, Jin and Yamada conducted a limited number of experiments to study the physical and physiological effect of smoke from fire evacuees [19]. They found that when in a non-irritant smoke, the walking speed of individuals decreased with increasing smoke density, such that with an optical density of 0.5 /m the working speed was decreased by over 75% and individuals behaved as if they were in total darkness. When exposed to irritant smoke, this effect occurred at even lower smoke concentrations. In order to simulate the smoke effect, Yuan and Tan incorporated tenability analysis into their CA model [20]. However, there is an unreasonable assumption in their research that is all evacuees in the compartment can see the exits clearly. Therefore, Yuan and Tan proposed another model to investigate the effect of visibility [21]. In their study, the human behaviour termed "flow with the stream" was also modelled. On the other hand, the visibility range was assumed to be constant in their model which may conflict with the reality. In this manuscript, an empirical method is adopted to estimate the visibility range so that the evacuation in a dynamical environment can be simulated. Based on CA model, the proposed model is implemented and verified by a numerical example.

2. Methodology

2.1. Calculation of visibility range

Visibility of exit signs, doors and windows can be of great importance to an individual attempting to survive of a fire. Visibility depends on many factors, including the scattering and the absorption coefficient of the smoke, the illumination in the fire room, whether the sign is light-emitting or light-reflecting, and the wavelength of the light [22]. Visibility also depends on the individual's visual acuity and on whether the eyes are "dark-adapted" or "light-adapted". It is reported that the visibility can be estimated by the following formula [23]:

$$R_V = \frac{cV}{K_m M_S} \tag{1}$$

where R_V represents the visibility measured in m. The term K_m is defined as the specific extinction coefficient, measured in m^2/g. M_S is the mass of smoke soot measured in g and c is a constant. Generally, $K_m = 7.6\ m^2/g$ is used for soot produced during flaming combustion of wood and plastics, whilst $K_m = 4.4^2/g$ is for soot produced during pyrolysis of these materials. The value of c is dependent on whether the sign is light-emitting or light-reflecting. For the former, $c = 8$, for the latter, $c = 3$. The letter V represents the volume of the space where the fire origin is. M_S can be calculated by Eq. (2) [24].

$$M_s = \varepsilon \cdot M \tag{2}$$

where M is the weight of burning material and ε is the smoke conversion factor.

According to Eqs. (1) and (2), the visibility range in a smoke-filled compartment is not constant if the soot concentration varies in the course of time. One may realize that it is possible to incorporate computational fluid dynamics (CFD) with Eq. (1). The history of M_S can be calculated by CFD software and thus a variational visibility range can be obtained.

2.2. Flow with the stream

"Flow with the stream" is regarded as a kind of human behaviour. This phrase is usually used to describe the psychological phenomenon that people intend to follow the lead of other people and react to their opinions or actions passively. During emergent evacuation, if it is hard to an individual to make a decision forthwith, for instance, he cannot see the exit in a smoke-filled compartment and he does not know where to move, he may decide to just follow the other people who are near to him.

In Fig. 1, the cells represent cellular automaton grid. The visible domain of an occupant at cell O is defined as the area surrounded by a circle with a radius denoted by R_V. It must be mentioned that R_V may not be constant in the course of time. For instance, it may be affected by smoke concentration in a fire compartment. To simulate "flow with the stream", it is assumed that this occupant cannot see the exit since it is outside of his visible domain. Without loss of generality, it is also assumed that there are N occupants within his visible domain, including the typical occupant denoted by i. According to CA model, each occupant at O has eight movement directions numbered from d_1 to d_8 at each time step. Similar to him, each of other occupants also has eight directions to move. Among all N occupants, it is assumed that the kth ($1 \leq k \leq N$) occupant is special since he knows where the exit is located. This occupant is defined as a guider in the proposed model and he is familiar with the fire compartment and the exit locations. The guider will lead other occupants to the exit although his visibility is also limited due to smoke. In such a situation, it is defined that this occupant at O determines his movement direction by following the rule termed "flow with the stream". The procedure is described below:

(1) At time t_i, check the status whether the occupant at cell O can see the exit. If it is true, the occupant will move towards the exit by comparing the importance of spatial distance and occupant density [16,20]. Otherwise, proceed to the next step.

(2) Check if there is a guider among the N occupants. If it is true, the occupant at cell O just follows the guider to move. Otherwise, proceed to the next step. If there are two or more guiders within the visibility domain, one of them will be chosen randomly to follow.

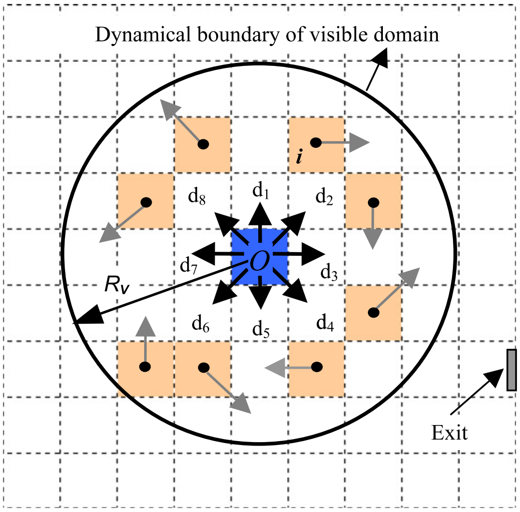


Fig. 1. Illustration of the determination of an occupant's movement direction.

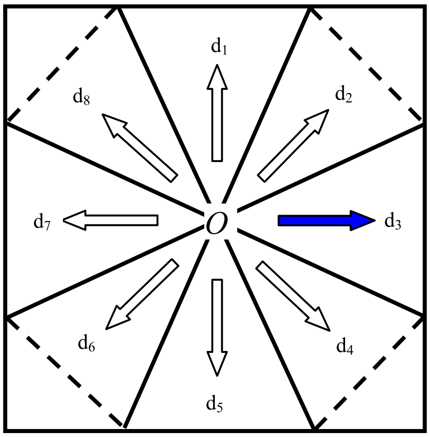


Fig. 2. Eight movement directions and the principal one.

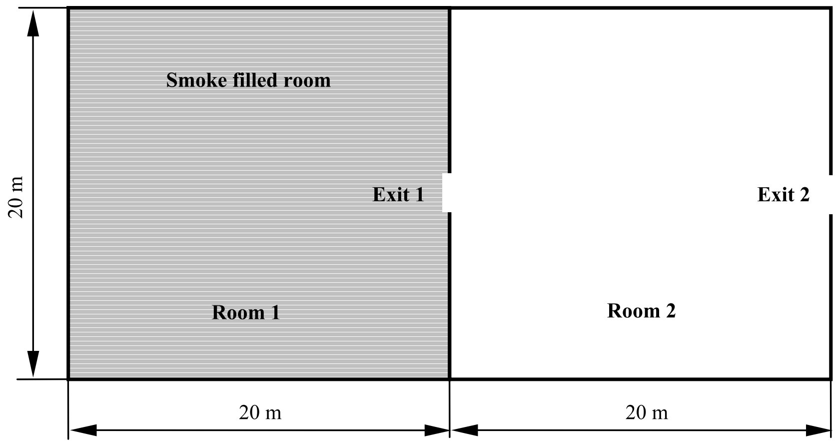
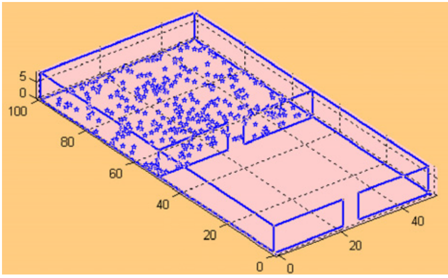
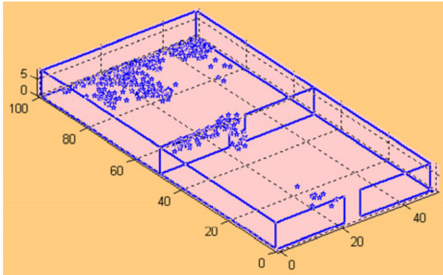


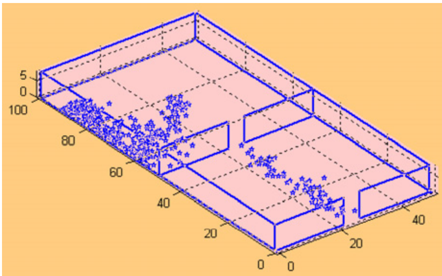
Fig. 3. A compartment with two square rooms.



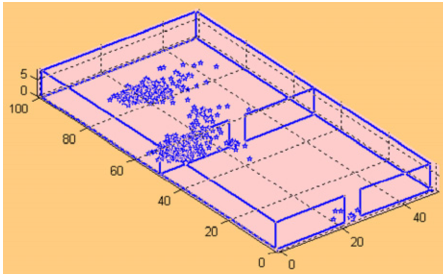
(a) Initial condition.



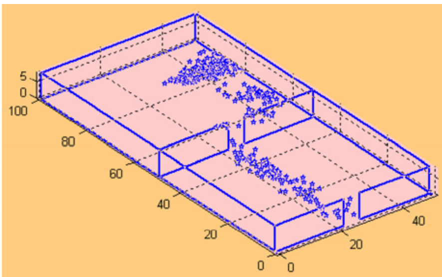
(b) 50th time step.



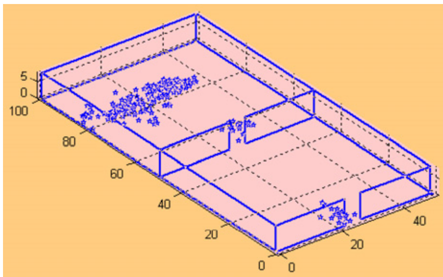
(c) 100th time step.



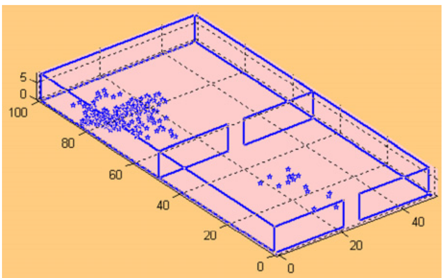
(d) 150th time step.



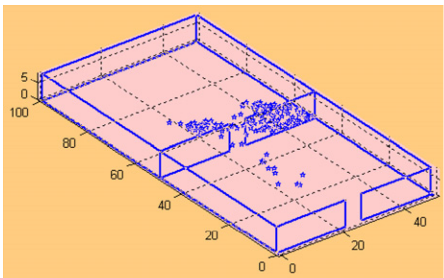
(e) 200th time step.



(f) 250th time step.



(g) 300th time step.

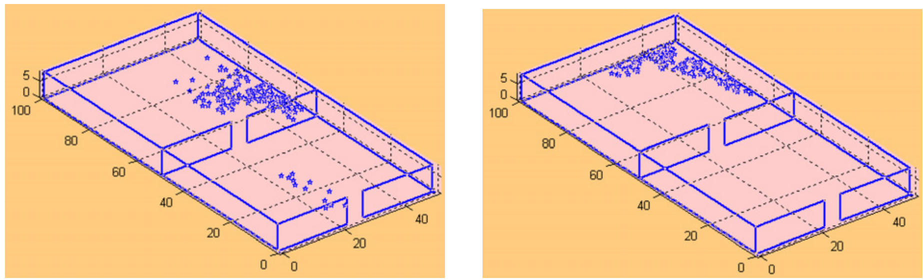


(h) 350th time step.

Fig. 4. The history of an evacuation from a two-room compartment: A trial run for Scenario 1.

(3) Based on the state at time t_{i-1}, count the number of occupants who are within the visibility domain and divide them into groups according to their movement directions. Since there are eight possible directions around the occupant at cell O, the maximum number of groups is also eight. Each group consists of several occupants who are moving in the same direction.

(4) The group which contains most occupants is defined as the leading group. The movement direction of the leading group is defined as the principal direction. If there are two or more leading groups (principal directions) around cell O, one of them will be chosen randomly to be followed by the occupant at cell O. For instance, in Fig. 2, it is assumed without loss of generality that the principal direction is d_3.



(i) 400th time step.

(j) 450th time step.

Fig. 4. (*continued*)

The way for the occupant at cell O to follow a guider or a group is described below:

(1) Select a target that might be followed, using the way provided in the four steps for "flow with the stream". The target can be a guider or a leading group.

(2) Once the target is fixed, the occupant has two options: (a) a probability of α is set for the occupant to give up following the target and moves along a direction selected randomly. (b) a $(1-\alpha)$ probability is set for the occupant to follow the target.

(3) If the occupant decides to follow the selected target, a probability of β is given to him to make himself closer to the target. When the target is a guider, the occupant will move towards the guider, but if the target is a leading group, the occupant will approach the centre of this group [16]. As a result, a $(1-\beta)$ probability is given to him to just move along the movement direction of the target. In this situation, he will not intend to shorten the distance between him and the target.

It must be mentioned that there is no certain way to determine the values of α and β. However, for a qualitative study, 0.2 is assigned to α and 0.3 is set to β in the present model.

3. Worked example

Fig. 3 shows the layout of a compartment that consists of two rooms. The height of the compartment is 3 m and the width of the two exits is 2 m. In this example, it is assumed that there is 1.0 kg polystyrene burning in flame in Room 1 so that this room is filled with smoke. Room 2 is assumed to be under normal condition.

3.1. Visibility range

The fire room forms a 20 m × 20 m × 3 m domain. By Eq. (2), the mass of smoke emission in Room 1 is:

$$M_s = 0.15 \times 1000 = 150\ \text{g}.$$

It should be noted that the smoke conversion factor for polystyrene is set to 0.15 in the calculation [23]. Hence, one can estimate the visibility range in Room 1 using Eq. (1):

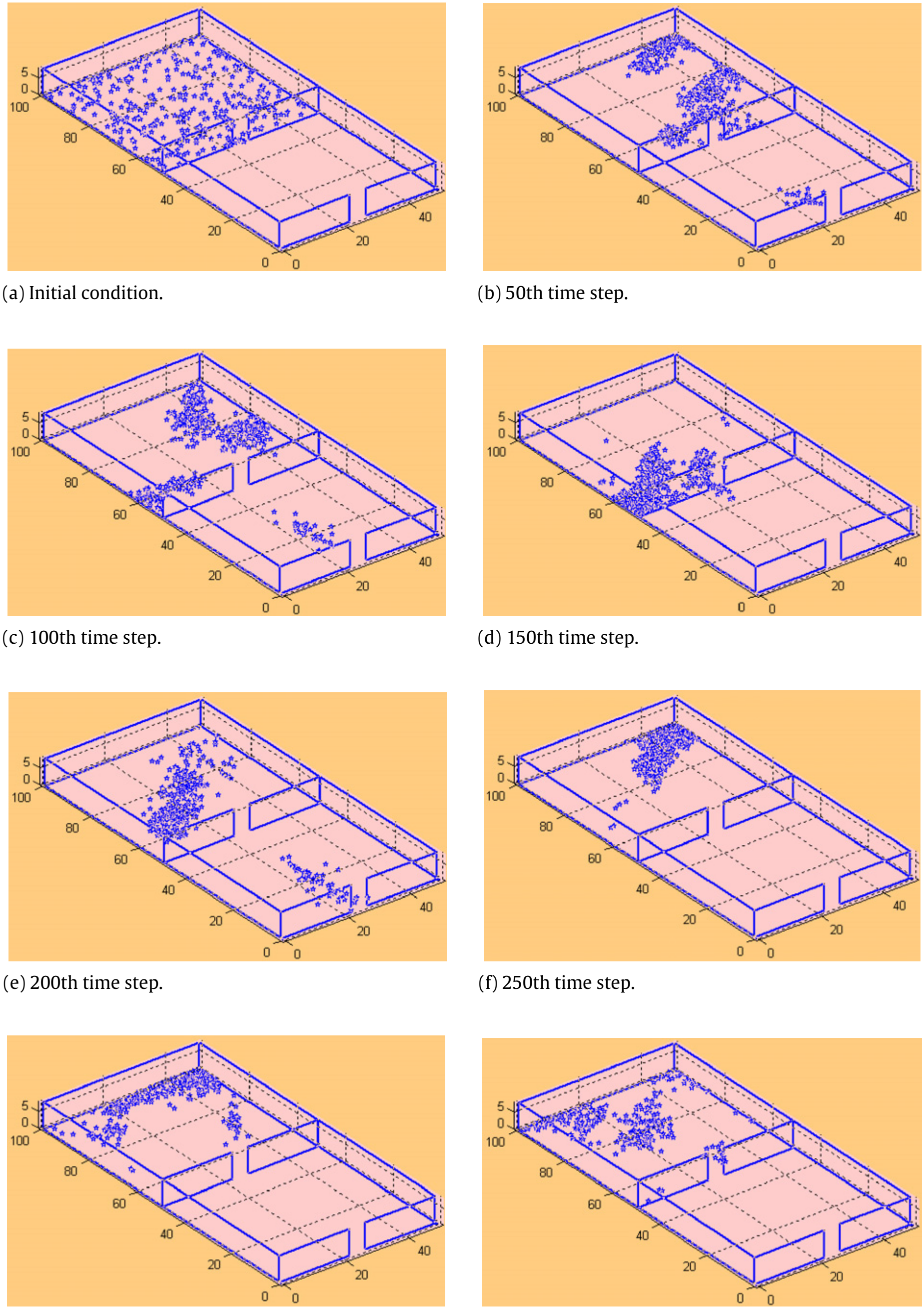
$$R_V = \frac{cV}{K_m M_S} = \frac{3 \times 20 \times 20 \times 3}{7.6 \times 150} = 3.2\ \text{m}.$$

It can be seen that the visibility range in Room 1 is 3.2 m. Meanwhile, the visibility range in Room 2 is assumed to be large enough for all occupants to see Exit 2.

3.2. Evacuation modelling

To use CA model, the compartment floor has to be meshed into a grid of CA cells. Each cell is 0.4 m × 0.4 m that is the typical space occupied by a person in a dense crowd [25]. It is assumed that there are 300 occupants in Room 1 before the evacuation starts. Although the visibility range in Room 1 is 3.2 m, it is easy to understand that the visibility range is not constant in reality. Therefore, to simulate a dynamical environment to verify the proposed CA model, two cases are considered for the visibility range in Room 1, viz. (1) the visibility range is always 3.2 m and (2) the visibility range changes linearly from 3.2 m to 2.0 m in a given period of time. Besides, in order to take the effect of guiders into account, two more cases, viz. with and without guiders need to be simulated. Thus, four scenarios listed below are generated for investigation:

(1) Scenario 1: Constant visibility range in Room 1, without guider R_V is always 3.2 m in Room 1. There is no guider among the occupants.
(2) Scenario 2: Constant visibility range in Room 1, with guiders R_V is always 3.2 m in Room 1. There are five guiders among the occupants. The guiders always know the locations of the exits and they evacuate with other occupants.
(3) Scenario 3: Variational visibility range in Room 1, without guider In Room 1, R_V decreases linearly from 3.2 to 2 m in 300 time steps (each step is equal to 0.29 s [20]). There is no guider among the occupants.



(a) Initial condition.

(b) 50th time step.

(c) 100th time step.

(d) 150th time step.

(e) 200th time step.

(f) 250th time step.

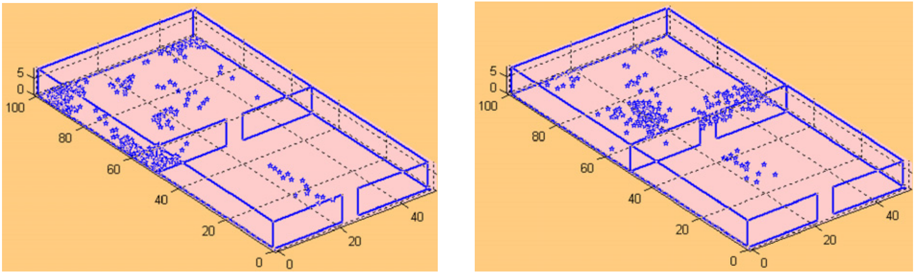
(g) 300th time step.

(h) 350th time step.

Fig. 5. The history of an evacuation from a two-room compartment: A trial run for Scenario 3.

(4) Scenario 4: Variational visibility range in Room 1, with guiders R_V in Room 1 decreases linearly from 3.2 to 2 m in 300 time steps. There are five guiders among the occupants. The guiders know the locations of the two exits very well and they evacuate with other occupants.

A trial run for Scenario 1 is demonstrated in Fig. 4. The entire modelling period is set to 500 time steps. At the beginning, all the 300 occupants are distributed stochastically in Room 1 (Fig. 4 (a)). After the evacuation starts, some occupants near to Exit 1 move towards the exit and evacuate from Room 1. Meanwhile, most occupants in Room 1 cannot see Exit 1 due to limited visibility. In this situation, they determine their movement directions by "flow with the stream". It can be seen from the evacuation patterns that several small crowds are formed during this procedure (Fig. 4(b)–(d)). The crowds explore



(i) 400th time step.

(j) 450th time step.

Fig. 5. (*continued*)

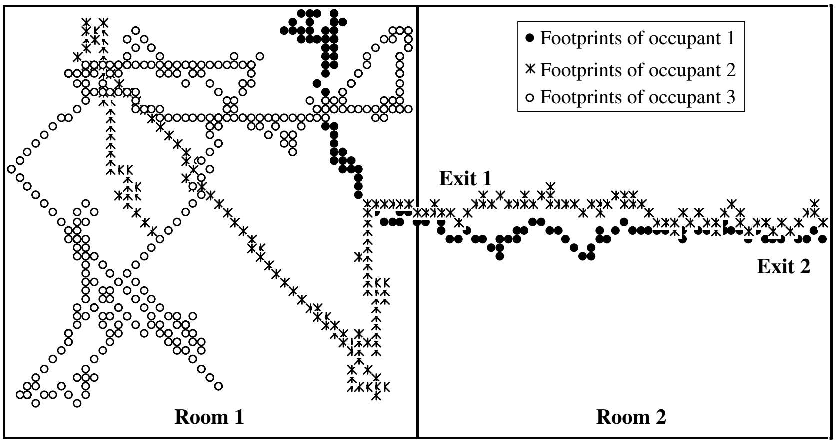


Fig. 6. The footprints of three typical occupants.

randomly in Room 1 for the exit until they see Exit 1 and evacuate to Room 2 (Fig. 4(e)–(h)). It can also be seen that some occupants cannot find Exit 1 in the given period of time (Fig. 4(i)–(j)).

A trial run for Scenario 3 is also conducted. Fig. 5 demonstrates the evolution of the evacuation in 500 time steps. It is found that the procedure is similar to that in Scenario 1. However, because the visibility range in Room 1 decreases to 2 m after 300 time steps, the evacuation in Scenario 3 looks more chaotic since it is harder for the occupants to find Exit 1.

The visibility effect can also be observed from Fig. 6. In a trial run for Scenario 3, the entire modelling period is still set to 500 time steps. Although there are 300 occupants distributed in Room 1 at the beginning, only three typical occupants are observed particularly in this trial. From the footprints plotted in Fig. 6, it can be seen that the initial location of Occupant 1 is not very far from Exit 1 so that he finds luckily the exit without much difficulty. However, due to limited visibility, Occupant 2 cannot find Exit 1 immediately, so he follows other occupants by "flow with the stream" and moves around in Room 1 until he enters Room 2 through Exit 1. The third occupant is unlucky. He traces an interlaced path in Room 1 but fails to evacuate in 500 time steps. The footprints in Room 2 also indicate that Occupant 1 and 2 approach Exit 2 straightly since their views in Room 2 are not affected by smoke.

Figs. 4–6 demonstrate that the proposed CA can be used to simulate the effect of visibility.

More simulations are conducted for the four scenarios. The number of occupants evacuated from Room 1 is investigated in each scenario. The entire simulation period is set to 350 time steps within which most occupants can evacuate from Room 1. It should be noted that CA is a nondeterministic approach. That is, for any of the four scenarios, different trial runs will present different results. Therefore, to obtain more general information, ten trial runs are conducted for each scenario and their mean value is recorded for use. The comparisons among the four scenarios are depicted in Fig. 7.

From this figure, two main conclusions can be obtained. The first one is that the effect of guiders is significant to the evacuation. It can be seen that the evacuation in Scenario 1 (no guiders) is slower than that in Scenario 2 (5 guiders). Similarly, the evacuation in Scenario 3 (no guider) is slower than that in Scenario 4 (5 guiders). Comparing the results for Scenarios 2 and 4, one finds that although the visibility conditions in these two scenarios are different, the two curves (in black) almost overlap at early stage and their difference becomes obvious only after 80 time steps. At the beginning of the evacuation, the guiders are all in Room 1. Because they are very familiar with the compartment, they always know where Exit 1 is located even though they may not be able to see it. In this situation, they can lead other occupants around them to the exit. During this period, the visibility effect is relatively weakened. However, after about 80 time steps, all the guiders have evacuated from Room 1 so that the remaining occupants have to look for the exit by the rule of "flow with the stream". In such a situation, the visibility range becomes a key factor that affects the evacuation. Therefore, the two curves separate after 80

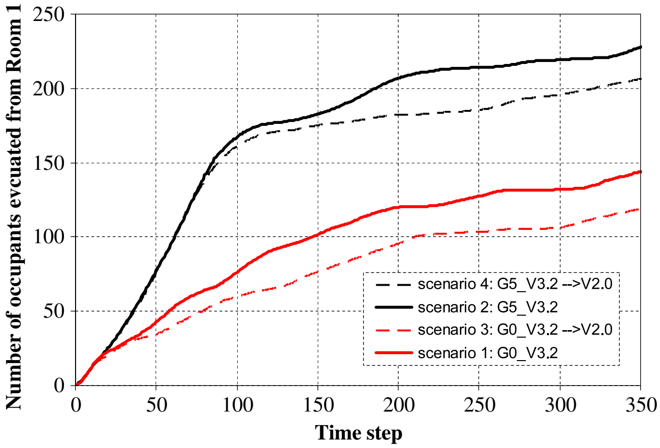


Fig. 7. The evacuation procedures of different scenarios. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

time steps. Because of the same reason, the difference between the two curves (in red) for Scenarios 1 and 3 appears at earlier stage as compared with that for Scenarios 2 and 4. Since there is no guider, the visibility ranges affect the evacuations from the beginning. The second conclusion is that decreasing visibility range can slow down the evacuation. As shown in Fig. 7, the evacuation in Scenario 1 (constant visibility) is faster than that in Scenario 3 (decreasing visibility), while the evacuation in Scenario 2 (constant visibility) is faster than that in Scenario 4 (decreasing visibility). The reason is that it is harder for an occupant to find the exit under lower visibility. Obviously, the above two pieces of conclusions agree with intuition. Therefore, the reasonableness of the proposed CA is verified.

4. Conclusion

In this study, a numerical model based on cellular automaton is proposed to study the visibility effect on evacuation. An empirical formula is adopted and incorporated into the CA model to estimate the visibility range. The psychological phenomenon termed "flow with the stream" is an important human behaviour that can affect evacuation significantly. Modelling of this phenomenon is a main objective of the proposed model. In reality the smoke concentration in a fire compartment may not be constant so that the proposed model is developed to deal with the case of variational visibility range. Additionally, the proposed model can also be used as a tool to investigate the effect of guiders through case study.

The implementation of the CA model is demonstrated by worked examples. The reasonableness of this model is verified by numerical results. Although the example presented in this study is very simple, it is believed that the proposed model has the potential to perform as a key component of an integrated CA frame work in the modelling of complex evacuation.

As reported, the walking speed of individuals decreases with increasing smoke density [19]. However, this fact is not considered in the proposed model. On the other hand, it is not difficult to take multi-velocity case into account if indirect algorithm is adopted [20].

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