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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 ($1 \le k \le N$) 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.