Physica A 461 (2016) 655–661

Contents lists available at ScienceDirect

Physica A

journal homepage: www.elsevier.com/locate/physa

A cellular automaton model for evacuation flow using game theory

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HIGHLIGHTS

- The effects of fear index and cost coefficient on the evacuation are studied.
- Some factors to prevent emergencies are investigated.
- Ratios of defectors to cooperators tend to consistent states.

ARTICLE INFO

Article history:
Received 25 January 2015
Received in revised form 4 September 2015
Available online 15 June 2016

Keywords:
Evacuation time
Cellular automaton
Game theory
Self-organization effect

ABSTRACT

Game theory serves as a good tool to explore crowd dynamic conflicts during evacuation processes. The purpose of this study is to simulate the complicated interaction behavior among the conflicting pedestrians in an evacuation flow. Two types of pedestrians, namely, defectors and cooperators, are considered, and two important factors including fear index and cost coefficient are taken into account. By combining the snowdrift game theory with a cellular automaton (CA) model, it is shown that the increase of fear index and cost coefficient will lengthen the evacuation time, which is more apparent for large values of cost coefficient. Meanwhile, it is found that the defectors to cooperators ratio could always tend to consistent states despite different values of parameters, largely owing to self-organization effects.

1. Introduction

During the process of evacuation of pedestrians, one of the most interesting and significant tasks challenging the researchers lies in the exploration of the mechanism of crowd conflicts, as well as some self-organization effects [1], which may contribute much to the guidance of pedestrian evacuation [2–6]. Many former research of pedestrian evacuation is based on microscopic models such as social force models, lattice gas models, cellular automata models, and so on. These models can to some extent describe many typical phenomena, for instance, clogging, arching, faster-is-slower, lane formation, and among others, which do occur in the process of real emergency evacuation. It is well known that pedestrian evacuation is a multi-agent complex system composed of pedestrians with strong interactions. In order to leave the hazardous place as soon as possible, evacuees try to seek their appropriate sites approaching the exit. In this process, conflicts will inevitably occur when two or more pedestrians choose the same site as their next moving step. With regard to this phenomenon, social force models, which are multi-particle self-driven continuous models based on Newtonian

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http://dx.doi.org/10.1016/j.physa.2016.05.062
0378-4371/

Table 1
The payoff matrix of the snowdrift game.

	C	D	E
C	(R R)	(S T)	(1 /)
D	(T S)	(P P)	(1 /)
E	(/ 1)	(/ 1)	(/ /)

mechanics, are well suited for the simulation of complex movements of pedestrians [1,7]. However, social force models are only applicable for a small scale of pedestrian evacuation due to calculation efficiency. While discrete models, such as lattice gas models and cellular automaton (CA) models, have no scale limitation owing to their special features. In recent decades, they have also been widely used to model some aspects of pedestrian dynamics [8–19].

In order to gain further insight into conflict behaviors caused by pedestrians, game theory is usually utilized in pedestrian evacuation. Indeed, game theory is acknowledged as a good tool to explore crowd conflict in the process of evacuation [20,21]. The complicated interaction force among pedestrians could be reflected by the payoff matrix, and the possible movement of pedestrians could be determined by their related payoffs [9,10].

Motivated by the above works, in this paper, we propose a CA model combined with game theory to simulate the process of pedestrian evacuation. We consider two important factors, namely, fear index and cost coefficient, in the proposed model. It is found from a large amount of numerical simulations that the increase of fear index and cost coefficient will lengthen the evacuation time, and this is more apparent for large values of cost coefficient. Moreover, during the evolution of pedestrian evacuation, it is found that arching phenomena are reproduced in this model and collective behaviors, also interpreted as self-organization phenomena, emerge in an evacuation flow. The remainder of this paper is structured as follows. In Section 2, the detailed model description is presented. In Section 3, a series of numerical simulations are given and the simulation results are analyzed. Finally, some concluding remarks are drawn in Section 4.

2. Model description

In our model, a room with one exit is considered. The room is described by a squared lattice with the size 10 m × 10 m. The exit is located at the center of the downward wall with the width 1.2 m. Each cell on the lattice can be empty, or occupied by a pedestrian, which size is designed as 0.4 m × 0.4 m according to the average size of human body. Each pedestrian always move towards the exit in evacuation without back steps. Walking across the wall is prohibited. Once the pedestrians arrive at the exit, they are eliminated from the lattice. The mean velocity of pedestrians is set as 1.3 m/s, i.e., moving 0.4 m at each time step $\Delta t \cong 0.3$ s. Two types of pedestrians are considered in this model, namely, cooperators "C" and defectors "D", which constitute the strategy set $\{C, D\}$. To simulate the effects of many subjective factors and to explore how two types of pedestrians compete for the empty site "E" approaching the exit, snowdrift game theory is suitably used to describe the complicated interaction among the conflict individuals. The payoff matrix of the snowdrift game is shown in Table 1, where $R = 1, T = 1 + r, S = 1 - r$, and $P = 0$ $(0 \le r \le 1)$ represent rewards, temptation, sucker's payoff, and punishment, respectively.

In order to make the model more realistic, we suppose that each centered evacuee is influenced by its eight nearest neighbors. In this case, a CA model with Moore neighborhood is used. In the CA model, the movement of an evacuee i is determined by static floor field $S_i(= 1/d_i)$, and d_i is calculated according to distance from the site i to the exit measured by a metric. Pedestrians always try to move from sites with smaller floor field to those with larger values.

Besides the above mentioned rules, some non-deterministic rules based on practical consideration are presented as follows.

(1) When pedestrian i has many nearby empty sites to choose, the transition probability of the person's movement to the empty site j is described by

$$P_e(i \to j) = \frac{\exp(k_s S_j)}{\sum_{l \in \Omega_i} \exp(k_s S_l)}, \tag{1}$$

where Ω_i denotes the position set of the evacuee's next accessible position (the empty site j included) toward the exit, and k_s is a scaling parameter, which reflects the evacuee's sense of distance from the exit. In fact, Eq. (1) reflects the evacuee's normal consideration that it is more likely for a person to choose the empty site nearer to the exit as the next target position in emergency evacuation.

(2) When the empty site j has many adjacent evacuees to fight for, conflict inevitably occurs. In this situation, the empty site j is occupied by the evacuee i according to the following probability

$$P_c(i \to j) = \frac{\exp(k_a U_i)}{\beta \sum_{i \in \Phi_j} \exp(k_a U_i)}, \tag{2}$$

where U_i denotes the average payoff received from the pedestrians of pedestrian i's neighborhood (U_i is calculated as follows: The total payoffs that the center pedestrian i gets from the neighborhood following the payoff matrix presented