A simulation model of pedestrian flow based on Bayesian Nash Equilibrium and a Multi-Agent System

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Summary

Agent-based modeling and simulation has become one of the mainstream approaches for research on pedestrian flows. This paper describes an evacuation simulation model of pedestrian flow based on a Muti-Agent System (MAS) and Bayesian Nash Equilibrium (BNE). BNE was adopted here to complement the rationality of pedestrian decision-making process during evacuation simulation, and MAS was used to simulate their movement and behaviors. Some self-organization phenomena (e.g. following/conformity behavior) were also included in this model. This paper provides a detailed introduction of the initial model and results and identifies several future directions.

KEYWORDS: Agent-based Modeling, Pedestrian Behaviors, Bayesian Nash Equilibrium, Emergency Evacuation, Pedestrian Movement

1. Introduction

Research on effective crowd management and evacuation planning has become increasingly relevant owing to the increasing number of public places where large crowds gather. There are a number of uncertainties associated with modelling pedestrian-related evacuation events (e.g. response times), and obstacles such as a lack of comprehensive data need to be overcome to support in-depth pedestrian studies. As a result, many field observations as well as theoretical analysis of pedestrian flows have been undertaken in recent years, with the aim of discovering the factors, parameters and rules of pedestrian flow states (Hwang et al., 2019; Feng et al., 2020).

As yet little research has considered the behavioral characteristics of pedestrian flow systematically, despite many studies examining individual behaviors as their objective (Babojelić and Novacko, 2020). One problem is the shortage of experimental data of individual behaviors, which can lead to a lack of effective guidance for crowd management and evacuation plans when disaster strikes (Feng et al., 2020). Consequently, developing an effective simulation model of pedestrian flow can be beneficial to establish large-scale crowd evacuation planning.

This paper proposes an evacuation simulation model of pedestrian flow based on Bayesian Nash Equilibrium (BNE) in a Multi-Agent System (MAS). The BNE is used to improve the rationality of pedestrian decision-making, and MAS is adopted to simulate the movements and behaviors of pedestrians. As this study is still as a primary stage, this paper mainly focuses on establishing the rules to underpin the simulation model for movement, individual decision-making and other behavioral aspects. A detailed introduction of the initial model is also provided.

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2. Research Progress[§]

2.1. Overview

This simulation model was constructed in Netlogo and took the Evacuation Decision-Making Crowd Model proposed by Van der Wal et al. in 2017 as a reference to simulate the movements of pedestrian flow during emergency evacuations.

2.2. Design Concepts

In this section, several self-processing rules for pedestrians in different scenes are defined.

2.2.1. Theoretical and Empirical Background

a. Basic Movement Rules

A pedestrian evacuation space was divided into square cells of 0.7m x 0.7m, and a simulation time step of 0.5s was set (Chang et al., 2021). Pedestrians were set to move at most one cell per time step during evacuations. They were permitted to move to one of the 6 candidate cells after their directions have been determined with associated probability distribution as shown as **Figure 1**. They were not permitted to move backwards.

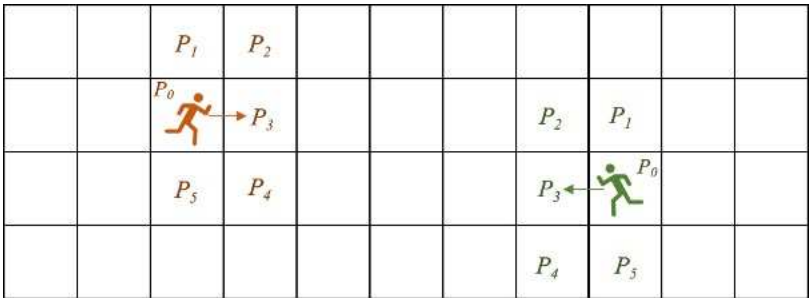

Figure 1 The probability distribution for the movements of two agents, one moving right the other moving left.

b. Pedestrian Speed-Density Relation

After investigation, the Spatial-Grid Evacuation Model (SGEM) (Lo et al., 2004) was considered the most appropriate pedestrian speed-crowd density model for this research. The speed-density relationship is shown as **Equation 1**.

$$v = \begin{cases} 1.4, 0 < \rho \leq 4 \\ 0.03\rho^2 - 0.64\rho + 3.36, 4 < \rho < 8 \\ 0.1, \rho \geq 8 \end{cases} \quad (1)$$

Where, ρ refers to the crowd density (person/m^2).

[§] ODD+D protocol (Müller et al., 2013) is adopted to describe the develop process of this simulation model. It is an extension of the original ODD (Overview, Design concepts and Details) protocol and takes the human decision-making into consideration.

2.2.2. Individual decision-making

Several theories have been developed around the rationality of pedestrian decision-making process during evacuation. BNE was adopted to overcome the propensity for a relatively uniform distribution of the pedestrians in evacuation space. It has a positive effect on evacuation time by avoiding large congestions.

a. Bayesian Nash Equilibrium

BNE is the equilibrium reached in a static game with incomplete information. It is defined as a strategy that can maximize the expected utility of the players who only know the probability distribution of the strategies played by other participants (Ui, 2016).

In this model, there is no sequence of decisions per time step, and no possibility for pedestrians to observe others' activities. Consequently, the "game" here is a static one with incomplete information and the equilibrium achieved is BNE.

b. Utility Function

The total utility of pedestrians during walking was divided into move utility U_m and comfort utility U_c (**Equation 2).**

$$U_{sum} = U_m + U_c \tag{2}$$

Where, *d* represents the distance traveled towards the exit, and θ is the angle between the exit and the moving direction of the agent. The term U_m (**Equation 3**) refers to the utility obtained by pedestrians during walking, and it grows in inverse proportion to the distance from the exit:

$$U_m = d \times \cos\theta \tag{3}$$

The term U_c (**Equation 4)** describes the number of pedestrians in one cell and equal to the proportion of the restricted speed to the free-moving speed.

$$U_c(n) = \begin{cases} 1.00, n \leq 2 \\ 0.51, n = 3 \\ 0.07, n = 4 \\ 0, n \geq 5 \end{cases} \tag{4}$$

Where, *n* represents the number of pedestrians in one cell. As the limited capacity of cells in reality, U_c was equal to 0 when there are over 4 agents in the same cell.

c. Expected Utility

Since the decision-making process of each pedestrian here is independent, the agent can only consider the probability of nearby agent decisions, and then calculate the expected utility of his/her each decision to find the cell with the maximum utility value. Each pedestrian can generally choose from 6 candidate cells per time step, and for each candidate cell, agents in eight adjacent cells have probabilities to enter the candidate cell (**Figure 2)**.

Figure 3 clarifies this: assume that several agents are randomly distributed, and it shows that when the blue cell (x, y) is selected as the target cell, how the agent (blue) competes with the nearby agents. The probability that agents enter cell (x, y) are also indicated.

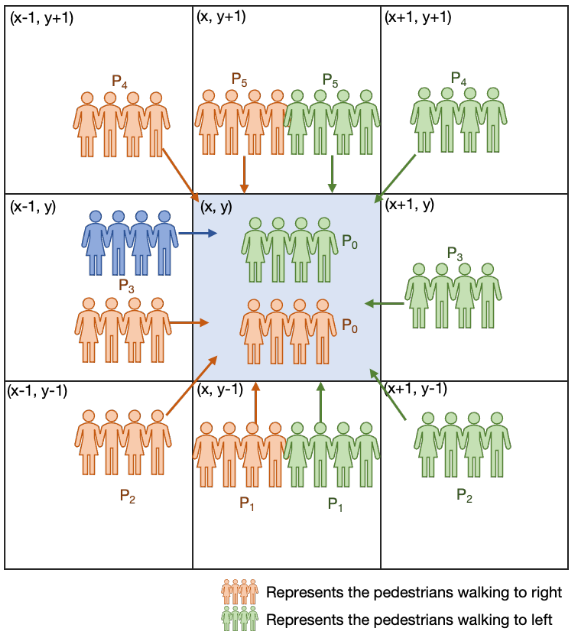

Figure 2 The diagram of agents monitored competing with nearby agents

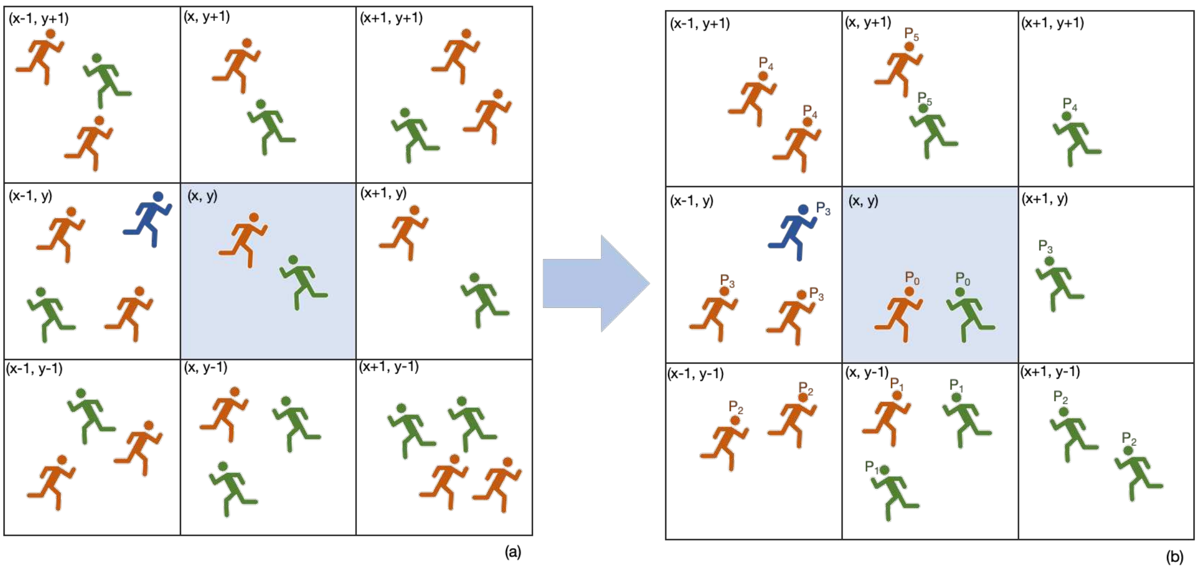

Figure 3 A detailed diagram of the agent (blue) competing with nearby agents

Therefore, the expected comfort utility of the agent monitored moving to cell (x, y) is shown as **Equation 5**:

$$\delta_c = \sum_{n=0}^{4} U_c(n+1)p(n) \tag{5}$$

Where, $p(n)$ represents the probability that the number of pedestrians in the candidate cell is *n*. Thus, the expected utility of an agent moving into a cell is the sum of U_m and δ_c.

d. Behavioral Rules

In this model, considering an agent with following behavior. It will have a preference for the three optional cells closest to the pedestrian being followed or the central location of the group being followed. This preference is represented by the weight coefficient A ($A \geq 1$), that is, when the pedestrian with following/conformity behavior chooses the preferred cell to move, the expected utility δ is shown as **Equation 6**:

$$\delta = U_m + A\delta_c \tag{6}$$

2.3. Details

2.3.1. Initializations

An initial model was coded in Netlogo with several fixed global variables at the initialization stage. Since it is not calibrated by any real data, the accuracy of global variables remains to be discussed. This initial model (**Figure 4)** assumes that the emergency happens in the middle of a tunnel and the pedestrians can evacuate through the two exits on either side of the tunnel.

Figure 4 The initial model

2.3.2. Implementation Details

Initial results (**Figure 5 & 6)** indicate the following behavior linked to BNE utility in the evacuation patterns. However, further model validation and sensitivity analysis are required.

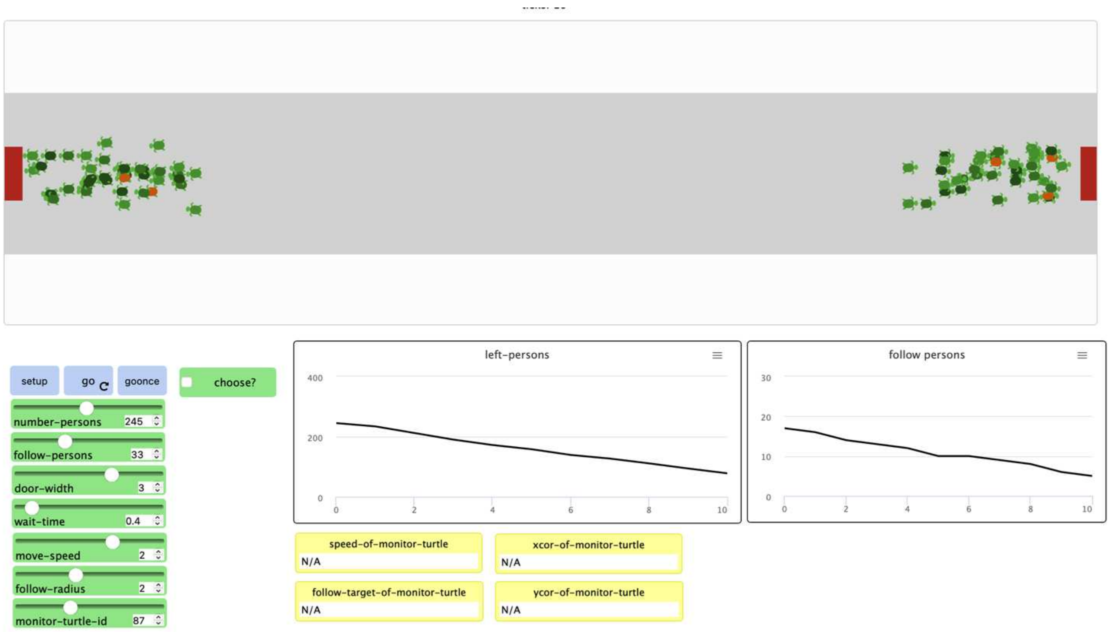

Figure 5 Model running without BNE (switch-off)

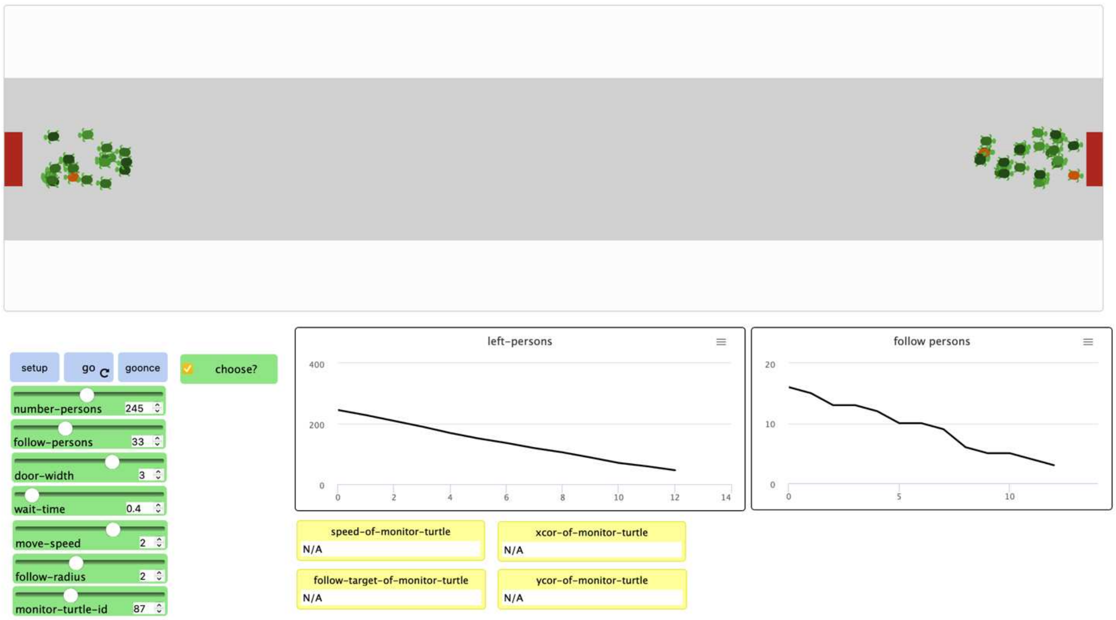

Figure 6 Model running with BNE (switch-on)

3. Conclusion and Further work

This research defines an evacuation simulation model of pedestrian flow based on MAS, and BNE. These were adopted here to complement the rationality of pedestrian decision-making process during evacuation simulation. Collision avoidance rules as well as following behaviors were also considered in this model. Future research will include greater pedestrian self-organization phenomena (e.g. competitive behavior, etc.) and other social factors (e.g. pedestrian emotions, etc.) to improve the simulation accuracy and efficiency of the model proposed.

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Biographies

Yiyu Wang is a PhD student in Center for Spatial Analysis and Policy (CSAP), at University of Leeds. Currently her research interests are the simulation of pedestrian behaviors under emergency evacuation applying agent-based modeling techniques, and their interactions with other social factors.

Dr Jiaqi Ge is a University Academic Fellow in the School of Geography in the University of Leeds. Her research areas are urban analytics and agent-based modelling. Her research develops agent-based models to analyze complex urban systems. For example, computational models have been developed to study the dynamic transition of urban systems under major social and economic shocks.

Lex Comber is Professor of Spatial Data Analytics, with research interests in all areas of spatial analysis and geocomputation. This year is he is mostly interested in search and optimisation methods for handling highly dimensional solution spaces in spatial problems.