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An evacuation simulation model of pedestrian flow using Bayesian Nash equilibrium and a Multi-Agent System

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Abstract. The shortage of experimental data for individual behaviours has hampered systematic research on pedestrian behaviours and the refined development of evidence informed rules for pedestrian movement in simulation models. This research proposes an evacuation simulation model of pedestrian flow based on Bayesian Nash Equilibrium (BNE) and Multi-Agent System (MAS). In this paper, BNE was used to augment the logics of pedestrian decision-making processes in an evacuation MAS simulation and to improve evacuating agents' movement and behaviours. A detailed introduction of the construction process and implementation details for the initial model as well as the visualization of experiment results are provided in this paper. Limitations and several potential future research directions are also identified.

Keywords. Pedestrian Behaviours, Agent Based Modelling, Bayesian Nash Equilibrium, Multi-Agent System

1 Overview

The ODD+D protocol (Müller et al., 2013) was used here to illustrate the specific process of model construction. It is a refinement of the original ODD (Overview, Design concepts and Details) protocol (Grimm et al., 2020) and introduces individual decision-making section to describe ABMs.

1.1 Purpose

The gathering of large crowds gathering is common in different public spaces. They may be subject to unexpected incidents and many studies have sought to improve the efficiency of evacuation planning to effective measures for large-scale crowd management (Babojelić and Novacko, 2020). However, in order to further develop research on pedestrian flows there is a need to overcome a series of obstacles such as shortage of evaluation data and uncertain pedestrian-related incidents (Shirvani et al., 2020; Wijermans and Templeton, 2022). To do this, much relevant theoretical research and field observations have been conducted so that regular patterns of pedestrian flow in different scenarios can be identified (Rozo et al., 2019; Feng et al., 2021). Despite of much research associated with individual behaviours, few systematic characteristics of pedestrian movement has been discovered (Babojelić and Novacko, 2020). One of the main barriers is the lack of experimental data that captures individual behaviours realistically, which may adversely affect the effectiveness of large- scale evacuation planning as well as crowd management.

This research aims to address the gap of a lack of experiment data on individual behaviours and to develop an effective simulation model for pedestrian flow in which individual evacuations are more realistic. To achieve this, Bayesian Nash Equilibrium (BNE) was introduced in the agent model to augment the simulation of pedestrian decision-making processes in an evacuation simulation within a Multi-Agent System (MAS) simulating pedestrian movement and behaviour in an evacuation. The construction details of the initial model will be introduced using the ODD+D protocol, and the visualization of experimental results will also be provided in the following sections.

1.2 Process Overview and Scheduling

In this research, MAS was adopted to simulate pedestrian movement and behaviour during emergency evacuation. From the perspective of the whole model, the related parameters of simulation environment as well as the characteristics of pedestrians were set in advance to establish the initial simulation space. With the exception of some fixed global variables, all other parameters (e.g. moving speed, sight range, ratio of agents using BNE, width of entrances, etc.) could be adjusted (via sliders in the NetLogo implementation). During the evacuation simulation, agents collect the environmental information and compete with other nearby pedestrians to choose an optimal evacuating route in each time step. This is an iterative process and stops when all the agents evacuate the simulation space.

From an individual perspective, Bayesian Nash Equilibrium (BNE) was introduced to prevent the propensity for a uniform distribution in the evacuation space and improve the representativeness of agent decision-making process during simulation experiments. Each agent considers the probability distribution of the strategies played by other nearby agents and find an appropriate evacuation route. Specifically, the agent calculates the expected comfort utility of all the neighbours who may compete with in the next time step, and combines it with the distance utility obtained during walking, in order to select one of the agents with maximum total utility to follow. In the next time step, agents repeat this process until they evacuate from the simulation space. A detailed introduction to the establishment of the initial model is provided in the following sections.

2 Design Concept

2.1 Theoretical and Empirical Background

BNE is generally defined as a strategy in which participants can maximize their own expected utility based on the probability distribution of the strategies played by other players (Ui, 2016). In other words, there is no restriction on sequence of participants' decision- making and the main element affected their behaviours is the proportions that other players will choose the same strategy.

On this basis, BNE was introduced into this model to augment the accuracy of pedestrian decision-making process in an evacuation simulation using a MAS to simulate evacuating pedestrian behaviours and movements.

2.2 Individual Decision-making

A detailed introduction to how the agent competes with its neighbours and then make its own decision is provided in this section.

Since BNE was adopted in the initial model to assist agents in finding an optimal evacuation route, each agent chooses their own decisions independently. In this research, BNE takes the form of a variable named "Total Utility" which is related to not only the distance from agents' current position to the exit but also the number of nearby agents in the same patch. The probability distribution of other agents' strategies $P_0, P_1, \ldots, P_5$, is also considered during evacuation simulation, impacting the patch density where the agent is located to a certain extent. In this condition, agents calculate the total utility of each neighbour and choose one of them with maximum value to follow. This process iteratively occurs per time step till the end of evacuation.

By default, reverse movement is not permitted here during evacuation simulation. And the agents are assumed to move at most one cell per time step, which also means that

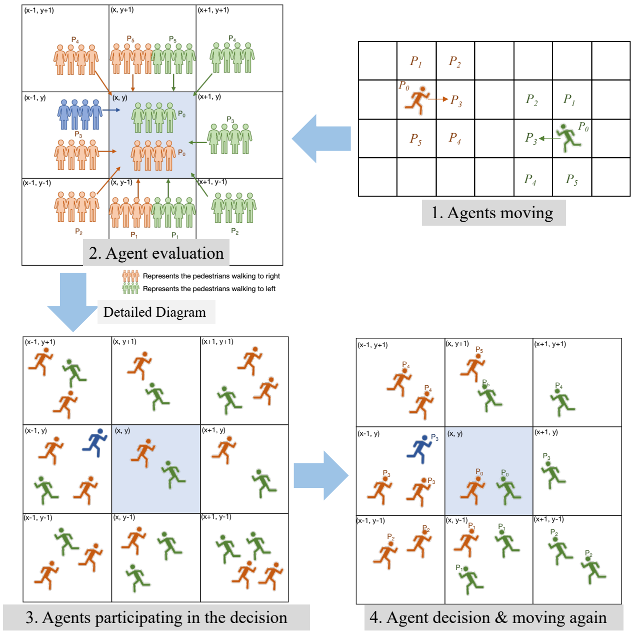

Figure 1. The schema of the agent (blue) completing with nearby agents

the competition only occurs in the nearby patches (9 candidate cells) of the target cell. Fig. 1 clarifies this: presuming that a few agents are randomly scattered, the schema illustrates that how the agent (blue) competes with other participants in one time step. Here, the blue cell (x, y) is chosen as the target and the proportion of agents entering cell (x, y) are also marked.

3 Details

3.1 Data and Software Availability

An initial model was coded in NetLogo of an emergency in of a tunnel and took the Evacuation Decision-Making Crowd Model developed by Wal et al. (2017) as a reference to undertake a series of simulation experiments for pedestrian movement in an emergency evacuation. At present, no input data is read in this model and the experiment results are exported from the NetLogo BehaviorSpace tool.

3.2 Initialization

The simulation model is initialized with a set of fixed global variables and presumes that agents can evacuate through the two exits on either side. At the initial stage, the agents are randomly distributed in the evacuation space, and a series of relevant variables (e.g. the number of agents and following targets, width of the exits, moving speed, sight range, etc.) are able to be adjusted through corresponding sliders to conduct simulation experiments under different conditions. In particular, the percentage of

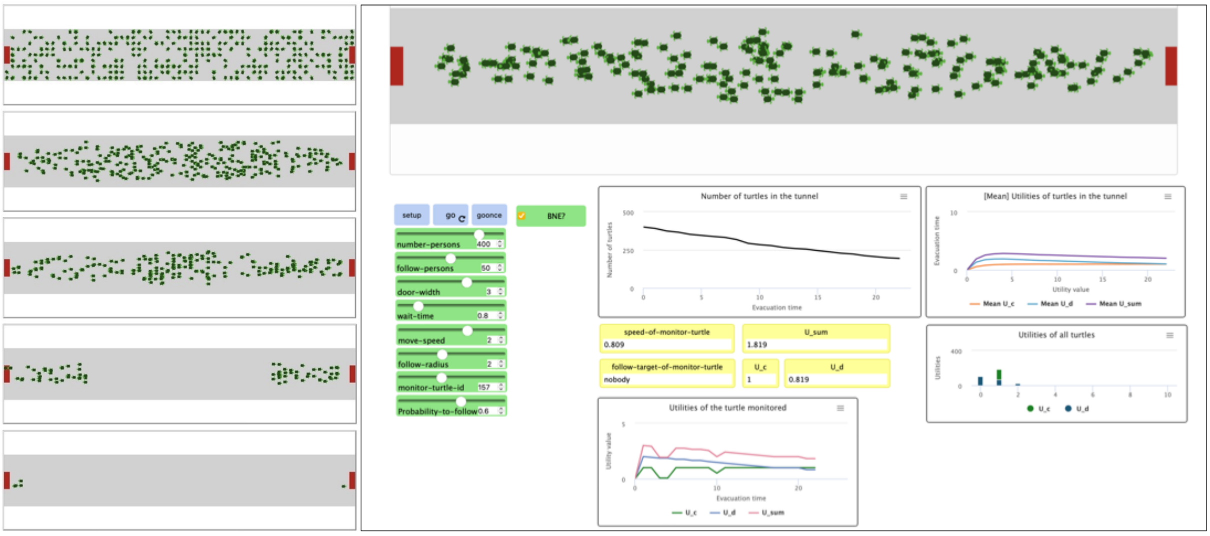

Figure 2. The main interface of the initial simulation model

agents using BNE during evacuation simulation can be regulated by the slider "Probability-to-follow". The agents using BNE compare the total utilities of each agent in surrounding patches and select one of the neighbours with maximum value to follow in each time step. The agents without the BNE function pick one agent in their sight range at random to follow at the beginning of the simulation. When there are no agents using BNE (i.e. the slider "Probability-to-follow" is set to 0), all the agents will randomly select another agent within their field of vision to follow. The main interface of model in NetLogo is shown as Fig. 2.

3.3 Submodels

3.3.1 Pedestrian Speed Setting

After investigating the related speed-density models, Spatial-Grid Evacuation Model (SGEM) proposed by Lo et al. (2004) was used to represent the relationship between pedestrian speed and crowd density in this research, since it takes account of the influence of the interactions among nearby pedestrians on the moving speed of the agent being monitored.

This model assumes that the pedestrian speed varies with the number of nearby agents. After considering real situations (Chang et al., 2021), the evacuation space here was divided into square cells of 0.49 m^2 ($0.7m$ x $0.7m$), and the parameters of original SGEM equation adjusted to adapt to the simulation environment, the new relationship is shown as Eq. (1).

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

Where, ρ represents the density of pedestrian ($person/m^2$). In this model, it equals to the number of agents in one patch over the patch area.

Furthermore, since the speed v_{move} can be regulated through the slider "move-speed", we assume that the speed remains proportional to the density in each time step, which means that the new equation reflecting the speed change is shown as Eq. (2).

$$V = \begin{cases} v_{\text{move}}, 0 < \rho \leq 4 \\ v_{\text{move}} \times \frac{(0.03\rho^2 - 0.64\rho + 3.36)}{1.4}, 4 < \rho < 8 \\ v_{\text{move}} / 14, \rho \geq 8 \end{cases} \tag{2}$$

3.3.2 Utility Calculations

The total utility of agents during evacuation simulation was associated with three main utility parameters: Distance Utility (U_d), Comfort Utility (U_c) and Expected Comfort Utility (U_c'). The total utility used for simulation is the sum of distance utility and expected comfort utility (see Fig. 3).

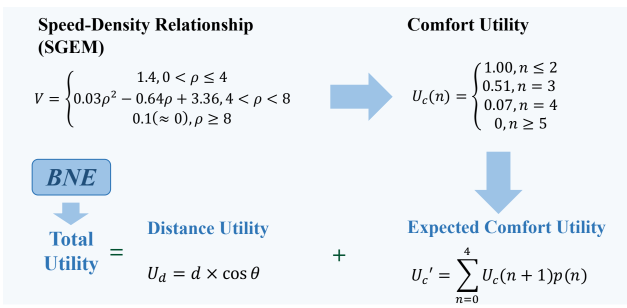

Figure 3. The diagram of BNE utility calculations

A. Distance Utility

It refers to the utility attained through walking and is inversely proportional to the distance from agents' current position to one exit, as illustrated in Eq. (3).

$$U_d(d,\theta) = d \times \cos\theta \tag{3}$$

Where, d refers to the distance to the exit and θ represents the angle of the agent's moving direction and the exit selected.

B. Comfort Utility

The term U_c is evolved from the pedestrian speed-density model and represents the comfortability of agents during evacuation. It is equivalent to the ratio of ordinary speed to the free-moving speed (1.4 m/s), as shown in Eq. (4).

$$U_c(n) = \begin{cases} 1.00, n \leq 2 \\ 0.51, n = 3 \\ 0.07, n = 4 \\ 0.00, n \geq 5 \end{cases} \tag{4}$$

Where, n describes the number of agents in the same cell. Due to the limited capacity in the real condition, U_c remains constant and equals to 0 when the number of pedestrians in one cell was over 4.

C. Expected Comfort Utility

Owing to the introduction of BNE, the agents' decision-making considers both the patch density (i.e. how many agents in its target cell) and the strategies played by the nearby participants in next time step. According to the probability distribution in Fig. 1, the expected comfort utility of the agent moving to cell (x,y) is shown in Eq. (5).

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

Where, $p(n)$ refers to the probability that the number of agents in the target cell (including the agent monitored) in next time step is equal to n.

4 Experimental Results and Discussion

NetLogo BehaviorSpace is introduced to evaluate the performance of the simulation model. During the "parameter sweeping" process, the model's configurations vary systemically, and the results of each model run was recorded. Specifically, the parameter of the proportion of agents using BNE during evacuation simulation is adjusted from 10% to 100% at intervals of 10%, and for each configuration, 10 repetitions were undertaken (i.e. the results of 100 runs are exported in this research).

Fig. 4 illustrates the variation of evacuation time with different percent of pedestrians using BNE to evacuate. Besides, the exit time when 70% to 99% agents evacuated was also recorded in this research.

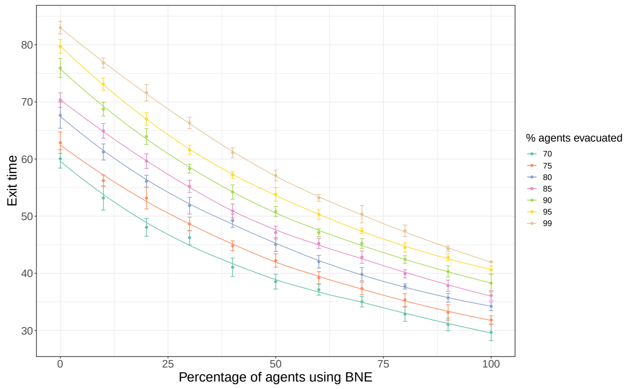

Figure 4. The changes of exit time with different percent of agents using BNE

The experiment results were trimmed and tuned to clearly reflect the effect of BNE function on pedestrian evacuation. Figs. 5 and 6 demonstrate the variations of mean comfort utility and mean expected comfort utility with different proportion of agents with BNE to select their evacuation path. The higher value represents that the pedestrians feel more comfortable during evacuation.

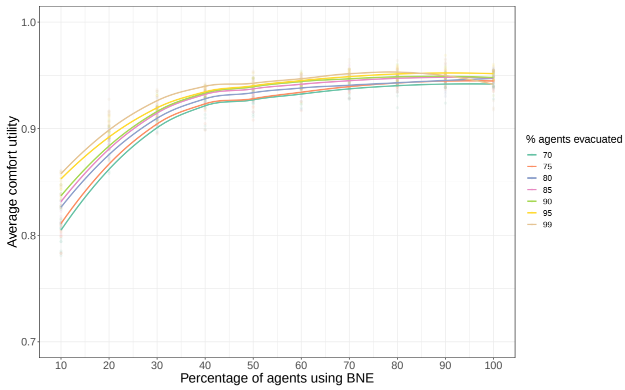

Figure 5. The changes of average comfort utility with different percentage of agents using BNE

As shown above, the reduction in exit time presents a linear relationship with the increase in ratio of agents using BNE function; and the relationship of average comfort utility/expected comfort utility and the percentage of agents with BNE can be described with a logarithmic curve. To be specific, when the proportion is over 40%, the comfort utility of agents remains constant at a relatively elevated level; when the proportion of agents with BNE continues to increase, the exit time persists declin-

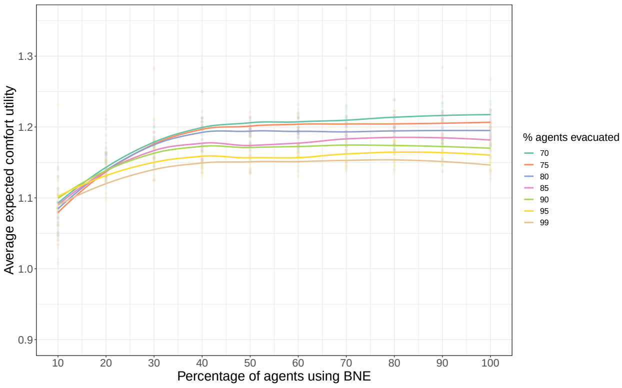

Figure 6. The changes of average expected comfort utility with different percentage of agents using BNE

ing while the mean comfort utility and expected comfort utility remains stable.

5 Conclusion

This research proposes an evacuation simulation model of pedestrian flow and BNE was introduced to augment the rationality of pedestrian decision-making process in an evacuation simulation using a multi-agent system to simulate evacuating pedestrian movement and behaviors. A series of experiment results were exported to evaluate the performance of the initial model. However, since there is no calibration with real dataset, the accuracy of global parameters remains to be confirmed. More experimental results with different parameter configurations need to be exported in the next step in this research to determine the parameter settings that the model perform best in its multi-dimension parameter space. Further research will also take account of greater pedestrian self-organized phenomena such as competitive behavior and social factors like panic to improve the simulation efficiency of the model.

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