A pedestrian evacuation ABM in a complex environment based on Bayesian Nash Equilibrium

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Summary

This research proposes an updated evacuation model incorporating Bayesian Nash Equilibrium (BNE) within multi-agent systems. It augments the rationality of pedestrian decision-making processes and improves the evacuating behaviours of pedestrians. Recent research found that BNE pedestrians could evacuate more quickly by avoiding clogged areas, closely matching the pedestrian evacuating behaviours in reality. This paper extends this work by introducing a number of diamond-shaped barriers in the model to evaluate whether and how BNE affects the pedestrian evacuation process in more complex scenarios. It provides a detailed introduction of the updated simulation model and identifies several limitations and potential research directions.

KEYWORDS: Bayesian Nash Equilibrium; Crowd Simulation; Barrier Avoidance; Agent-based Modelling; Pedestrian Evacuation.

1. Overview

Recent research has proposed a behavioural model that incorporates Bayesian game theory within multi-agent systems (i.e. BNE model) to fill the gap of lacking representative and forward-looking behavioural models in ABMs for pedestrian evacuation. BNE pedestrians were found to evacuate faster since they can regulate their directions and avoid the most clogged areas by predicting local congestion levels around them at every time step, closely matching the evacuating behaviours in reality (Wang et al., 2022).

To further evaluate whether this BNE model was adaptable to other types of pedestrian simulations (e.g. flooding or fire), a series of diamond-shaped barriers were placed on the original evacuating routes of BNE agents to discover whether and how BNE could affect the movements and behaviours of evacuating agents in multi-agent systems to more realistically simulate the pedestrian behaviours as well as individual decision-making process in complex scenarios. In this paper, the implementation details of the updated model are described following ODD+D protocol (Müller et al., 2013). The analysis of initial results as well as research directions for next step have also been provided.

2. Design Concepts

2.1. Theoretical Background

The refined Bayesian Nash Equilibrium proposed by Ui (2016) loosened the restrictions on complete information and started considering a game with incomplete information. This is aligned with the context of emergency evacuations in which complete real-time information may often be missing for individuals. BNE is generally regarded as a strategy in which players can maximize their own expected

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utility based on the probabilities of the strategies played by other players. That is, the crucial factor in deciding the next actions is the probability distribution of other nearby players making the specific choices. In this research, BNE is effectively the calculation of total utility in agents' decision-making process.

2.2. A BNE model for pedestrian decision making in a complex environment

To convert the BNE theory into concrete decision-making rules, a series of utility functions were introduced into the model in order to implement a BNE behavioural model. As there is no specific sequence of participant decision-making in a BNE game, agents following BNE in this research make their decisions only based on the value of *Total Utility* of candidate patches.

Total Utility is related to three parameters: *Distance Utility* (U_d), *Comfort Utility* (U_c) and *Expected Comfort Utility* (U_{ec}). That is, BNE agents determine their next actions after considering the distance to the exits, the number of agents on the same patch as themselves, and the potential movements of agents on their Moore neighbourhood[§] (Wang et al., 2022). So far, reverse movement has not been permitted in this model. This model allows each patch to be occupied by more than one agent per time step, making it probable that a crowd of agents may gather during evacuation. BNE was introduced to quantify the individual decision-making and BNE agents can avoid the most clogged patches by predicting the actions of the other agents in their Moore neighbourhood. Specifically, each BNE agent will compare the total utilities (i.e. sum of U_d and U_{ec}) of the five candidate patches in front (see **Figure 1**) and decide where to move. The calculations of the relevant utilities are shown as **Figure 2**.

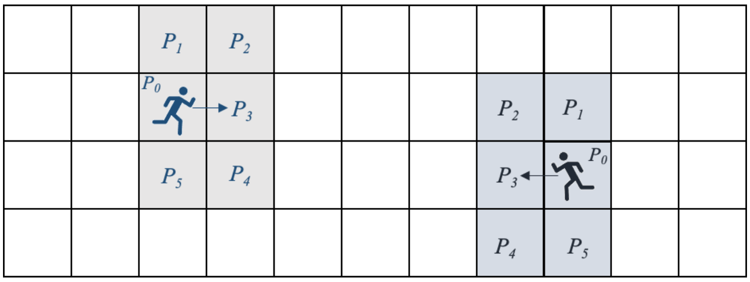

Figure 1 Candidate patches for agents moving rightward and leftward.

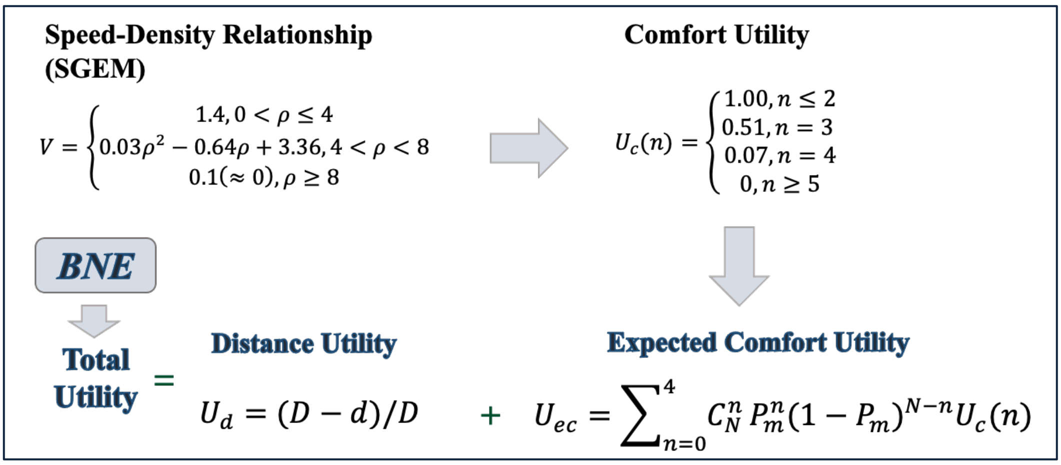

Figure 2 Calculations of BNE utilities

[§] Refers to a square-shaped neighbourhood with radius of 1 cell.

In the initial model, all the BNE agents tended to choose the patch with highest total utility to move (i.e. 100% best choices). This basic criterion was adjusted to a decision-making combination: with 50% BNE agents making the optimal choice (i.e. patches with highest total utility), 40% suboptimal choice (i.e. patches with second-highest total utility) and 10% choosing one of remainder of the candidate patches. The aim was to address the issue of small-scale congestion caused by the same decisions made by BNE agents in the latter half of the evacuation simulations.

3. Model Details & Analysis

3.1. Implementation Details

The initial model was developed using Java in NetLogo. The source code and experimental data have been published on COMSES and the used version is archived at https://doi.org/10.25937/75wf-aa82 . The updated model for this paper is still being developed and will be released once it is finished.

The model space was initialized with 2000 agents scattered randomly over the simulation space and the assumption that the agents were able to evacuate through the two exits on either side. The simulation environment was made up of 1360 (68*20) patches, and each of them can be occupied by one or more agents. The speed of each agent depends on the number of agents on its Moore neighbourhood (i.e. crowd density) and the reference speed can be adjusted.

In order to test the efficiency of BNE in different environments, the evacuation behaviours of 100 % BNE agents were observed in a more complex and challenging simulation environment. The updated model introduced the random placement of an assigned number of diamond-shaped blockades (i.e. Von Neumann Neighbourhood of range *r*[**]) over the evacuation space, with the radius of blockades (*r*) able to be adjusted. For each patch, its total utility was calculated at the beginning and updated over the simulation run. To efficiently avoid barriers, the movement rules for BNE agents were improved to a decision combination: 50% BNE agents making the best choice, 40% BNE agents making the second-best choice and 10% choosing one of the rest strategies.

3.2. Results

To appraise whether and how BNE affects pedestrian evacuation behaviours in complex scenarios, the whole evacuation process was recorded and the model views were also exported every 20 ticks during simulation (see **Figure 3**). The blue patches represent the barriers and the red ones are exits. As shown, BNE agents can avoid the impassable areas and the most clogged patches by predicting the congestion level around themselves in next time step. The observed number of agents declines linearly over time which reveals in part that no large-scale congestion occurred during simulation (see **Figure 4**). It was also reflected in the variation of average expected comfort utility referring to the overall mean of U_{ec} recorded every time step: this stable trend indicates that BNE agents remain a relatively steady comfort level during evacuation (see **Figure 5)**. Agents gathering together leads to a smaller value of average U_{ec}, namely a relatively low comfort level, which was undiscovered during the evacuation process.

[**] Refers to a diamond-shaped neighbourhood with a radius of *r* cells, which is generally used to define a set of cells surrounding a given cell in a CA model.

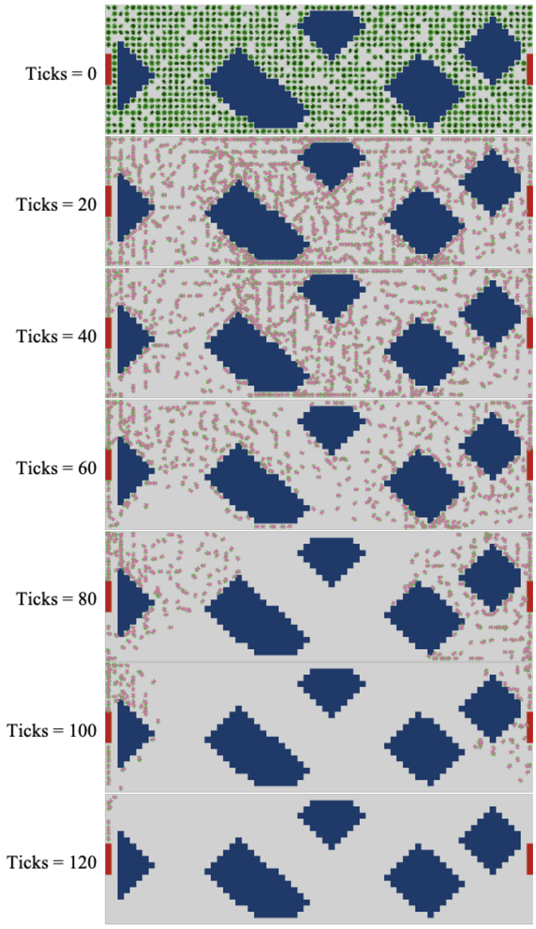

Figure 3 The stages of the flow of BNE agents evacuating from complex space.

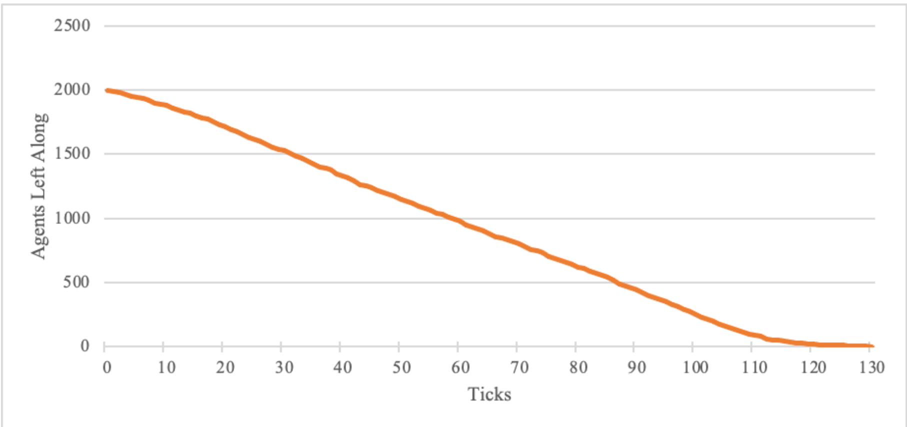

Figure 4 The number of agents left along during evacuation.

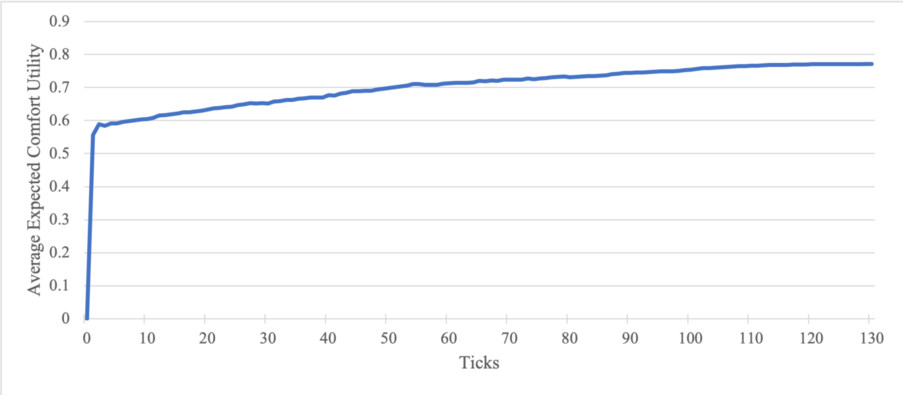

Figure 5 The variation in average expected comfort utility of BNE agents during evacuation.

4. Discussion & Conclusions

This research proposed an evacuation model that incorporate Bayesian Nash Equilibrium within multi-agent systems with the purpose of providing more realistic simulations of evacuating behaviours in complex scenarios. A series of diamond-shaped barriers were introduced in the initial model and movement rules for BNE agents were also improved to match the demand for barrier avoidance during evacuation. It was hypothesized that compared with other traditional models in the field, agents following BNE model could display a more forward-looking evacuating behaviours not only in normal simulation environments but also in more complex ones. Thus far, the evacuation process of 100% BNE showed good results when a number of blockades were introduced. The comfort level remains in a relatively stable trend during simulation. That is, BNE still has positive impacts on pedestrian evacuations even in the scenarios involving a series of blockades.

However, several issues still need be handled in the further work: 1) Lack of Comparisons: the BNE model still needs to be compared with other existing models such as A* searching algorithm in the field in order to further evaluate its performances; 2) Limited Scope: the paper focuses solely on pedestrian evacuation in certain complex environments (e.g. flooding and fire), and it would be beneficial to broaden the study scope to other areas, such as traffic congestion or public transport systems to provide a more comprehensive assessment of the BNE model's effectiveness; 3) Lack of Real-world Data: some real-world datasets are required in the next step to validate the results of the BNE model and ensure that it accurately represents the evacuation behaviours in reality; 4) Future Directions: A series of simulation experiments need to be conducted using different movement combinations and percentages of BNE agents. Different types of barriers and corridors should also be considered to determine the universality of using a BNE behavioural model in pedestrian research. These issues will be addressed in the next step of this ongoing research.

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Biographies

Yiyu Wang is a PhD student in Centre for Spatial Analysis and Policy (CSAP), at University of Leeds. Currently her research interests are the forward-looking simulation model of pedestrian evacuating behaviours under emergency incorporating Bayesian game theory within multi-agent systems, 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 analyse 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 he is mostly interested in methods for handling spatial scale and for supporting different scales of decision making.