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A pedestrian ABM in complex evacuation environments based on Bayesian Nash Equilibrium

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Abstract. This research proposed an improved pedestrian evacuation ABM incorporating Bayesian Nash equilibrium (BNE) to provide more realistic simulations of evacuating behaviours in complex environments. BNE theory was introduced to improve the rationality of model simulations by quantifying individual decision-making process. Latest research put forward that BNE pedestrians (agents) were capable of evacuating faster and displayed more intelligent and representative evacuating behaviours. To further evaluate the role of BNE played in agents' navigations in complex scenarios, this paper extends the above work by introducing impassable barriers with changeable sizes to realise the simulations in a more complex evacuation space with several narrow corridors. In order to match the demands of efficiently avoiding congestions and impassable areas, the decision-making rule of BNE agents when one patch was occupied by over 10 agents was improved from 100% best strategy to a multi-strategy combination: with 50% optimal strategy, 40% suboptimal strategy and 10% choosing one of the remaining options. It was found that compared with the agents following the other two traditional models, BNE agents could change their original exiting route after considering possible movements of the neighbouring agents and may evacuate through the corridors relatively further from the exit. A detailed introduction of the improved ABM is provided in this paper. Potential research directions are also identified.

Keywords. Agent-based Modelling, Pedestrian Evacuation, Bayesian Nash Equilibrium, Crowd Simulation, Pedestrian Behaviours.

1 Overview

Recent research has proposed a pedestrian evacuation ABM that integrates Bayesian game theory to address the lack of forward-looking and representative individual behavioural models in pedestrian evacuation simulations. The model was shown to contribute to more efficient and intelligent evacuating behaviours by forecasting congestion levels at every time step, indicating that such models can better represent individual evacuating behaviours in real-world scenarios (Wang et al., 2022c).

This study aims to further assess the applicability of the Bayesian Nash Equilibrium (BNE) behavioural model in other pedestrian simulation studies involving complex scenarios, such as fire and flooding. To achieve this, this study develops an improved simulation model with initial barriers designed to increase the evacuation difficulty. The paper follows the ODD+D protocol (Müller et al., 2013), which brought individual decision-making section into the ODD (Overview, Design concepts and Details) protocol (Grimm et al., 2020), to introduce the implementation details of the updated model. A discussion on potential research directions is also provided.

2 Design Concepts

2.1 Theoretical Background

The proposed model utilises a refined version of BNE by Ui in 2016, which accounts for incomplete information, closely matching the fact the pedestrians may miss some real-time information in a real-world evacuation scenario. BNE is a strategy profile that maximises the expected utilities of players based on the probabilities of other players' next movements (Ui, 2016). Thus, the probability distributions of nearby agents' future actions, along with a set of utility formulas, are the critical components of individual decision-making logic in this model. The basic equations for this model are provided below.

2.2 Behavioural Models for Pedestrian Decision-making in complex environments

In this model, agent decision-making processes are modelled at the individual level and depend on their allocated behavioural model. Three behavioural models been implemented in the improved model: Shortest Route (SR), Random Follow (RF) and BNE.

2.2.1 Shortest Route Model

Dijkstra's search algorithm was introduced to replace the weak SR strategy (i.e. the Euclidean distance between exits and current locations) in the initial model (Wang et al., 2022b) so as to consider the congestion costs during evacuation. NW extension [1], a NetLogo tool with commands and reporters in Java following Dijkstra's algorithm, was used in the improved model to realise the decision logic of SR agents who always follow the shortest route avoiding barriers during evacuation.

2.2.2 Random Follow Model

The RF model designates a set number of evacuees as leaders at the start of simulations. The remaining evacuees randomly choose a leader to follow, seeking to gather around the closest leader who knows the shortest evacuation path. The evacuation movement of RF leaders follows the laws of the SR model. Followers will find a new leader once the previous one is out of sight, and this process repeats until the end of the simulation.

2.2.3 Improved BNE model

This research adopted BNE theory to quantify individual decision-making processes in pedestrian evacuation. Formulas for utility calculations were introduced to implement the BNE behavioural model in an ABM. Since players in a BNE game are considered to make their decisions out-of-sequence, BNE pedestrians in this research determine their next actions hinging on the value of Total Utility for optional patches.

Total Utility (U_{total}), which is relevant to Distance Utility (U_d), Comfort Utility (U_c) and Expected Comfort Utility (U_{ec}), defined as the sum of U_d and U_{ec} (see Eq. (1)). BNE agents use this parameter to select an optimal path after considering the distance to the exit, congestion levels, and possible movements of agents in their Moore neighbourhood [2]. They are able to avoid congestions by predicting the actions of agents in their Moore neighbourhood. The total utilities of the five optional patches in front of each BNE agent are evaluated to determine the optimal path for the next time step (see Fig. 1).

$$U_{total} = U_d + U_{ec} \tag{1}$$

[1]The complete documentation of NetLogo NW extension is available at https://github.com/NetLogo/NW-Extension.

[2]Moore neighbourhood: refers to a square-shaped neighbourhood with radius of 1 cell.

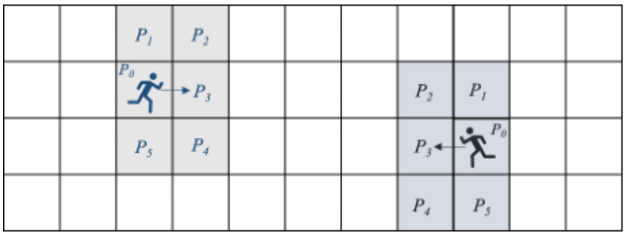

Figure 1. Candidate patch-set for agents moving rightward and leftward.

All equations related to BNE utilities are provided as follows.

- ***Distance Utility***

The term U_d refers to the distance from the current position to the exit and is set to an increasing parameter value closer to the exit, as illustrated in Eq. (2).

$$U_d = (D - d)/D \tag{2}$$

Where, d represents the distance to the exit and D is the diagonal distance of the simulation space.

- ***Comfort Utility***

The term U_c refers to a series of coefficients which is a primary element of U_{ec}, representing individual comfort level in every patch. It is set to be in an inverse proportion to the number of agents occupying the patch, as shown in Eq. (3).

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

Where, n means the number of agents on the patch.

- ***Expected Comfort Utility***

The term U_{ec} is a patch attribute and regarded as the multiplication of U_c and the probability $p(n)$ that a certain number (n) of agents move to this candidate patch in next time step, accounting for the possible actions of agents on itself as well as its Moore neighbourhood.

$$\begin{aligned} U_{ec} &= \sum_{n=0}^{4} p(n) U_c(n) \\ &= \sum_{n=0}^{4} C_N^n P_m^n (1 - P_m)^{N-n} U_c(n) \end{aligned} \tag{4}$$

Where, n refers to the number of agents on this patch; N represents the total number of agents on this patch and its Moore neighbourhood; P_m refers to the probability of agents moving to this patch, defaulting to 50%.

The initial implementation of BNE used a decision-making criterion that all agents selected the patch with the highest U_{total} (i.e., 100% of agents making best choices). However, the experimental results showed that this led to an issue that BNE agents on the same patch might make the same decisions in the latter half of simulations, resulting in small-scale congestions and lower exiting speed. To address this issue, the decision logic was updated to a multi-strategy combination where, if a patch is occupied by over 10 agents, 50% of BNE agents on itself select the patch with the highest U_{total}, 40% select the patch with the second highest U_{total}, and 10% choose one of the remaining optional patches.

3 Model Details and Analysis

3.1 Data and Software Availability Section

The model is developed in NetLogo. The initial version of the source code and experimental data have been published on COMSES and available at https://doi.org/10.25937/75wf-aa82 (Wang et al., 2022a). The improved model for this paper is still being developed and will be released once finished.

3.2 Initialisation

The model was initialised with 2000 agents randomly scattered throughout the simulation space. It was hypothesised that each agent would use their own behavioural model to avoid barriers and evacuate through the exit on the right side. Four different behavioural patterns were provided: Shortest Route (SR), Random Follow (RF), BNE mixed with SR, and BNE mixed with RF. The RF pattern included 400 leaders (i.e. 20% of the total), and this percentage could be adjusted through the input pane. The default percentage of BNE agents was 100% in the last two BNE combinations, but the mixing proportions could be adjusted as needed.

The evacuation environment consisted of 1360 patches with multi-occupancy allowed, making it possible to observe how agents following different behavioural models handle the congestions on their evacuation route. The speed of each agent was updated based on the number of agents in its Moore neighbourhood, with the speed-density relation following the Spatial-Grid Evacuation Model (SGEM) (Lo et al., 2004). The speed regulations depended on the reference speed assigned at model initialisation, where individual moving speed was inversely proportional to the number of neighbouring agents.

To evaluate the evacuation efficiency of BNE in complex scenarios, pedestrian evacuating behaviours were observed in a simulation space containing three narrow corridors formed by two large rectangular barriers. The improved model allowed for the placement of oblong blockades to create narrow passageways and decreased the number of exits to one. BNE-related utilities were defined as patch attributes in this model, with U_{total} calculated at the beginning of simulations and updated every time step. The decision-making logic of BNE agents was improved from 100% best strategy to a multi-strategy combination to match the demands for the avoidance of barriers and congestions during evacuation.

3.3 Expected Results

To evaluate the impacts of BNE on pedestrian evacuating behaviours in complex scenarios, the evacuation process of three behavioural models was recorded at 20-tick intervals and presented in Fig. 2 for the first 100 ticks. The blue and red patches respectively denote blockades and exits. The results reveal that all agents can avoid impassable areas regardless of the behavioural model they follow, and the congestion levels in the SR and RF models are more severe than in BNE. The majority of SR agents tend to evacuate through the middle corridor, causing large-scale congestions, while a similar phenomenon is observed in the RF pattern since the leaders accounting for 20% of the total follow the SR model. Other RF agents randomly follow one of the leaders, resulting in crowd gathering and queuing during evacuation. BNE agents can predict the congestion level in the next time step, enabling them to avoid the most clogged area. Consequently, BNE agents located relatively far from the exit can change their original route after considering the possible movements of other neighbouring agents and evacuate through the corridors located on either side.

It is also found that SR agents take longer time to evacuate when the corridors are widened. A rational explanation is that large-sized blockades have a positive impact on SR agents' evacuating as the pedestrians are forced to exit through the other two corridors instead of the one with shortest distance to the exit. A series of experiments involving varying widths of narrow corridors are required in further study.

4 Discussion and Conclusion

This paper presents an improved evacuation model that incorporates Bayesian Nash Equilibrium (BNE) within multi-agent systems, with the goal of simulating realistic evacuating behaviours in complex environments. The study hypothesizes that BNE agents display more representative and forward-looking behaviours in both simple and complex evacuation scenarios, owing to their ability to predict the possible actions of neighbouring agents and se-

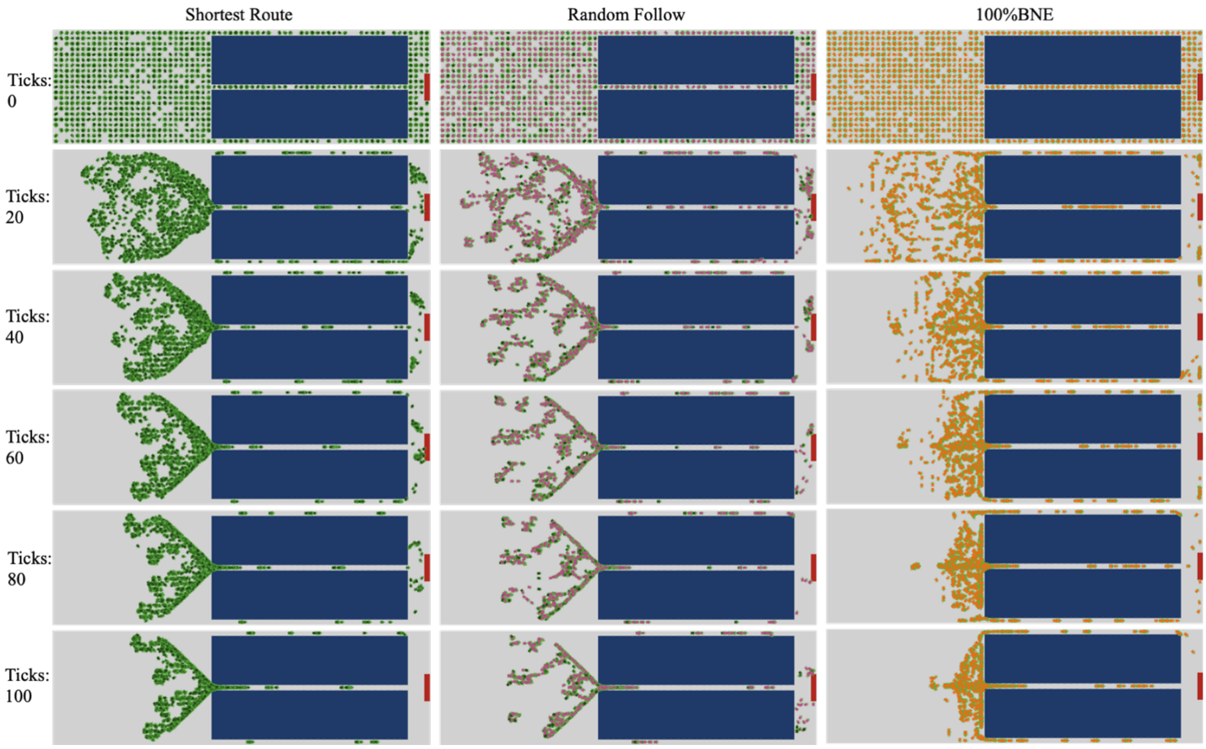

Figure 2. The stages of the flow of agents following three behavioural patterns: SR, RF and 100%BNE).

lect a faster exiting route with lower congestion levels. The model introduces a series of barriers of adjustable sizes to form narrow corridors, thus enabling a more comprehensive assessment of the efficiency of BNE in pedestrian evacuation.

To address the challenges of congestions and barriers, this paper improves the decision-making rules of BNE pedestrians when more than ten agents occupy the same patch, allowing for a multi-strategy combination of selecting the optimal and sub-optimal strategies and randomly selecting an unoccupied neighbouring patch. The results show that BNE agents play a positive role in pedestrian evacuation, even in the presence of impassable barriers, by selecting routes that maybe relatively further from the exits to prevent from being trapped in the congestions.

However, the feasibility of applying the BNE behavioural mode in other complex environments requires further evaluation. The research also proposes the need for simulation experiments with varying types of barriers and various mixing proportions of BNE-SR/RF combinations to comprehensively assess the evacuation efficiency of BNE in complex evacuation scenarios.

References

Grimm, V., Railsback, S. F., Vincenot, C. E., Berger, U., Gallagher, C., DeAngelis, D. L., Edmonds, B., Ge, J., Giske, J., Groeneveld, J., Johnston, A. S., Milles, A., Nabe-Nielsen, J., Polhill, G., Radchuk, V., Rohwäder, M.-S., Stillman, R. A., Thiele, J. C., and Ayllón, D.: The ODD Protocol for Describing Agent-Based and Other Simulation Models: A Second Update to Improve Clarity, Replication, and Structural Realism, Journal of Artificial Societies and Social Simulation, 23, 7, https://doi.org/10.18564/jasss.4259, 2020.

Lo, S., Fang, Z., Lin, P., and Zhi, G.: An evacuation model: the SGEM package, Fire Safety Journal, 39, 169–190, https://doi.org/https://doi.org/10.1016/j.firesaf.2003.10.003, 2004.

Müller, B., Bohn, F., Dreßler, G., Groeneveld, J., Klassert, C., Martin, R., Schlüter, M., Schulze, J., Weise, H., and Schwarz, N.: Describing human decisions in agent-based models – ODD + D, an extension of the ODD protocol, Environmental Modelling Software, 48, 37–48, https://doi.org/https://doi.org/10.1016/j.envsoft.2013.06.003, 2013.

Ui, T.: Bayesian Nash equilibrium and variational inequalities, Journal of Mathematical Economics, 63, 139–146, https://doi.org/https://doi.org/10.1016/j.jmateco.2016.02.004, 2016.

Wang, Y., Ge, J., and Comber, A.: An agent-based simulation model of pedestrian evacuation based on Bayesian Nash Equilibrium" (Version 1.0.0), CoMSES Computational Model Library, https://doi.org/10.25937/75wf-aa82, 2022a.

Wang, Y., Ge, J., and Comber, A.: An evacuation simulation model of pedestrian flow using Bayesian Nash equilibrium and a Multi-Agent System, AGILE: GIScience Series, 3, 68, https://doi.org/10.5194/agile-giss-3-68-2022, 2022b.

Wang, Y., Ge, J., and Comber, A.: An agent-based simulation model of pedestrian evacuation based on Bayesian Nash Equilibrium, arXiv preprint, https://doi.org/arXiv:2211.14260, 2022c.