Navigation in Complex Space: An Bayesian Nash Equilibrium-Informed Agent-Based Model

Yiyu Wang
School of Geography, University of Leeds, UK

Jiaqi Ge
School of Geography, University of Leeds, UK

Alexis Comber
School of Geography, University of Leeds, UK

Abstract

This study proposed an improved pedestrian evacuation ABM employing Bayesian Nash Equilibrium (BNE) to simulate more realistic and representative individual evacuating behaviours in complex scenarios. A set of vertical blockades with adjustable gate widths was introduced to establish a simulation space with narrow corridor and bottlenecks and to evaluate the influences of BNE on individual navigation in complex space. To better match with the evacuating behaviours in real-world scenarios, the decision-making criterion of BNE evacuees was improved to a multi-strategy combination, with 80% of evacuees taking the optimal strategy, 15% taking sub-optimal strategy, and 5% taking the third-best one. The preliminary results demonstrate a positive impact of BNE on individual navigation in complex space, showing a distinct decrease of evacuation time with increasing proportion of BNE evacuees. The non-monotonicity of the variations in evacuation time also indicates the dynamic adaptability of BNE in addressing immediate challenges (i.e. blockades and congestions), which identifies alternative and potential faster paths during evacuations. A detailed description of the proposed ABM and an analysis of relevant experimental results are provided in this paper. Several limitations are also identified.

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Category Short Paper

1 Introduction

Recent research has proposed a novel ABM for pedestrian evacuation which employs Bayesian Nash Equilibrium (BNE) to fill the gap of lacking representative and forward-looking individual behavioural models in relevant research on pedestrian evacuating simulations [5]. This ABM has been shown to be capable of producing more realistic individual evacuating behaviours in simple scenarios because evacuee agents following the BNE model are able to predict future congestion levels at each time step to find faster evacuation routes. The experimental results suggest that such model could better represent the real-world evacuating behaviours and improve the effectiveness of emergency management strategies.[5]

On this basis, this study aims to further evaluate the influences of the BNE model on individual navigation in complex spaces as well as its applicability in pedestrian simulations involving different scenarios. The above initial work has been extended by improving the decision-making logic of the initial BNE model in order to adapt to the evacuations in complex environments. An improved BNE-informed ABM has been developed in NetLogo with a series of vertical blockades with adjustable gate width brought into the simulation space to form complex evacuation scenarios. A series of simulation experiments were conducted to examine how and whether the updated model plays roles in individual evacuation process in these complex spaces. The implementation details of this improved model, the analysis of the experimental results, as well as a discussion on limitations and further work have been provided in this paper.

2 Methodology

2.1 Theoretical Background

This research adopts a refined Bayesian Nash Equilibrium (BNE) [3] as the underlying theory of individual decision-making. BNE is a gaming strategy in which the players maximise their expected utilities and take the best strategy according to the probability distribution of other players' next decisions [1]. The BNE refinement takes incomplete information into account, which aligns with the situation in which some real-time information might be ignored by some pedestrians in real-world evacuation scenarios [3]. The proposed model embodies BNE as a set of utility functions and considers the probability distributions of neighbouring evacuees' further actions, to provide a more accurate representation of individual decision-making process in a complex evacuation scenarios, with potential applications in optimizing evacuation plannings in different scenarios.

2.2 Improved BNE Model

Bayesian Nash Equilibrium (BNE) was employed as a methodological framework to quantify the individual decision-making process in complex evacuation space. A series of utility functions have been incorporated into the improved ABM to implement the BNE behavioural model. Due to the non-sequential decision-making in BNE games [3], the evacuees following BNE model determined their future actions based on the values of Total Utility (U_{total}) for their neighbouring patches.

The concept of Total Utility (U_{total}) is associated with three crucial factors: Distance Utility (U_d), Comfort Utility (U_c), and Expected Comfort Utility (U_{ec}), and designated as the total value of U_d and U_{ec}, as represented by Eq. (1) [5]. This parameter, which value considers the distance to the exit, future congestion levels, and possible actions of other evacuees in their Moore neighbourhood[1], is participated in the decision-makings of BNE evacuees' next movements. That is, evacuees following BNE model are capable to avoid congested areas by forecasting possible movements of other nearby evacuees. For each BNE evacuee, the total utilities of all the passable patches in its Moore neighbourhood are calculated and compared to determine the favourable patch to move at the next time step (see Fig. 1). The BNE-related functions are described as follows.

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

A. Distance Utility. U_d is associated with the distance between an evacuee's current position and the exit. It should be noted that the patches representing impassable barriers are not included in related calculations. The value is defined by a monotonically increasing function that approaches the maximum as evacuees are close to the exit point, as shown in Eq. (2).

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

[1] Moore Neighbourhood: a square-shaped neighbourhood with radius of one cell.

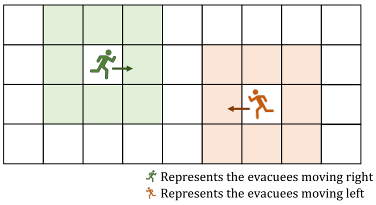

Figure 1 The candidate patches of BNE evacuees.

Where, d represents the distance of the shortest route from the current location to the exit; D denotes the diagonal distance of the evacuation space.

B. Comfort Utility. U_c comprises a set of coefficients which is a fundamental component of U_{ec}. Its value is determined by the number of evacuees occupying the given patch and reflects the individual comfort level of this patch. An inverse relation can be found between the value of U_c and the crowd density of the certain patch, as illustrated 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 represents the number of evacuees on the patch.

C. Expected Comfort Utility. U_{ec} is calculated as the product of two elements: Comfort utility U_c and the probability $p(n)$ that a particular number (n) of evacuees will move to the appointed patch at next time step, as shown in Eq. (4). The calculation of $p(n)$ considers not only the future movements of the evacuees on this patch, but also the possible actions of those located on the Moore neighbourhood.

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

Where, n represents the count of evacuees on the patch at next time step; N denotes the total number of evacuees located on the patch and its Moore neighbourhood at this time step; P_m represents the probability of evacuees who may move to this patch at next time step, with a default value of 50%.

2.3 Improvement Details

In the initial implementation [5], the BNE model employed a decision-making criterion that required all the evacuees to choose the patch with maximum U_{total}, resulting in 100% of evacuees taking the best strategies. However, the experimental results indicated that this criterion could lead to all BNE evacuees located on the same patch making identical choices in the latter stages of simulations, which, in turn, resulted in localized congestion and reduced exiting speeds [5]. In this paper, this challenge is addressed by including some noise to the initial decision-making logic of BNE evacuees, by switching to a multi-strategy combination: with 80% of evacuees taking the optimal strategy (i.e. selecting the patch with highest U_{total}), 15% taking the sub-optimal strategy (i.e. choosing the patch with second-highest U_{total}), and 5% making the third-optimal choice (i.e. selecting the patch with third-highest U_{total}).

As well as the improved BNE model, two other behavioural models are included – Shortest Route (SR) model (Dijkstra's search algorithm [2] was introduced to replace the weak SR strategy) and Random Follow (RF) model – as control groups in the proposed ABM to better evaluate the performances of BNE model [5].

3 Experimental Results

3.1 Model Initialisation and Implementation Details

The initial version of the BNE-informed ABM was developed in NetLogo and published at COMSES, which was retrieved from `https://doi.org/10.25937/75wf-aa82` [4]. The improved version is still in process and will be available once completed.

The initial configuration of the improved ABM involved the random dispersion of 2000 evacuees (agents) throughout the simulation space to the left side of the vertical blockades. The main purpose of this research is to explore the influences of different behavioural models on individual evacuating behaviours, with a specific focus on the capability of BNE evacuees to discover faster evacuation routes in order to navigate around congested areas and the barriers on their pathways. To achieve this objective, four distinct movement patterns were provided, including Shortest Route (SR), Random Follow (RF), BNE mixed with SR, and BNE mixed with RF. The percentage of BNE evacuees defaults to 100% in the last two BNE combinations, and the mixing ratios could be adjusted to meet the requirements of simulations.

To assess the effects of BNE on individual navigation in complex space, this paper conducted a simulation study where the individual evacuating behaviours could be observed in an evacuation space consisting of a narrow corridor defined by two vertical rectangular blockades with an adjustable-width gate for each barrier. All BNE-related utilities were computed at the beginning of each simulation and updated every time step. The decision-making criterion of BNE evacuees has been improved from a single strategy to a multi-strategy combination to better simulate the individual navigation in complex space with blockades, bottlenecks, and congestions.

3.2 Simulation Experiments

A set of experiments simulated evacuations in a tunnel space consisting of vertical barriers with adjustable-sized gates. The model was initialized with 2000 evacuees, where the BNE evacuees were mixed with evacuees adhering to one of the other two behavioural models (i.e. SR and RF). The proportion of BNE agents was adjusted from 0% to 100% at 2% intervals, and the gate width for each blockade varied from 1 to 9 at 2-patch intervals. The simulations were replicated 10 times for each parameter configuration and stopped once all agents evacuate successfully through the exiting point. The exit time of each simulation was recorded to evaluate the impacts of BNE on individual evacuations in complex space.

3.3 Result Analysis

Fig.2 illustrates the variations in evacuation time of the evacuees following BNE with SR and with RF combinations respectively in a complex space with varied width of gates. A local line of fit with 95% confidence interval was also generated in the plots to reflect the relationship among exit time, percentage of BNE evacuees, and sizes of the barriers. As shown, there is little advantage of specifying BNE when the gate width of blockades is too narrow, while a decreasing trend of evacuation time with increasing proportion of BNE evacuees can be observed in the scenarios with wider gates. That is, a positive impact of BNE on shortening evacuation time becomes salient as the increasing percentage of BNE agents participating into the simulations.

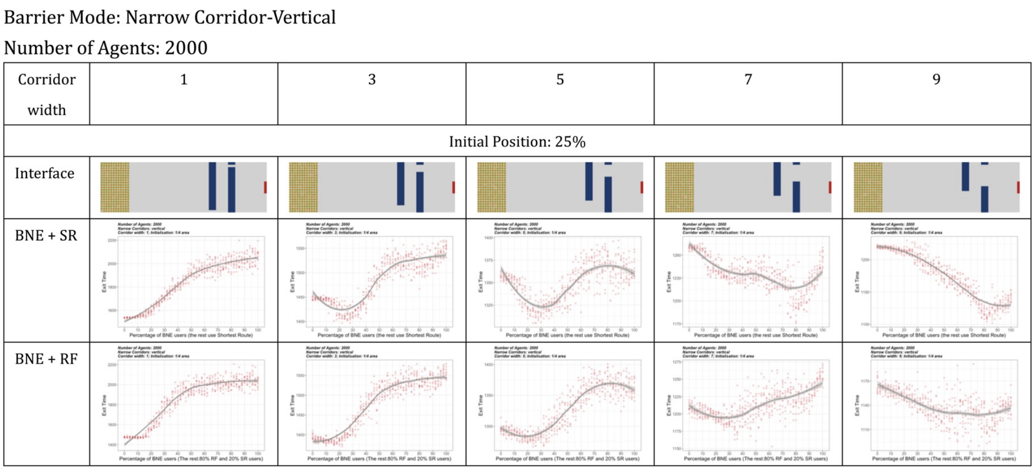

Figure 2 Evacuation time against percentage of BNE-SR and BNE-RF combinations in complex scenarios with varied width of gates (2000 evacuees).

The non-monotonic changes of exit time against the two BNE combinations in complex scenarios are worthy of further discussion. A reasonable explanation for this phenomenon is that some of BNE evacuees may be trapped in the corner of the corridor as a queue of evacuees following other models was formed during evacuations. As shown in Fig.3, evacuees adhering to SR model (shown in green) were observed to follow an identical trajectory to avoid barriers and evacuate. The consistency of path selection may lead to a situation that BNE evacuees (shown in orange) were confined within the corridor as SR evacuees were stuck at the bottlenecks resulting in a heavy congestion.

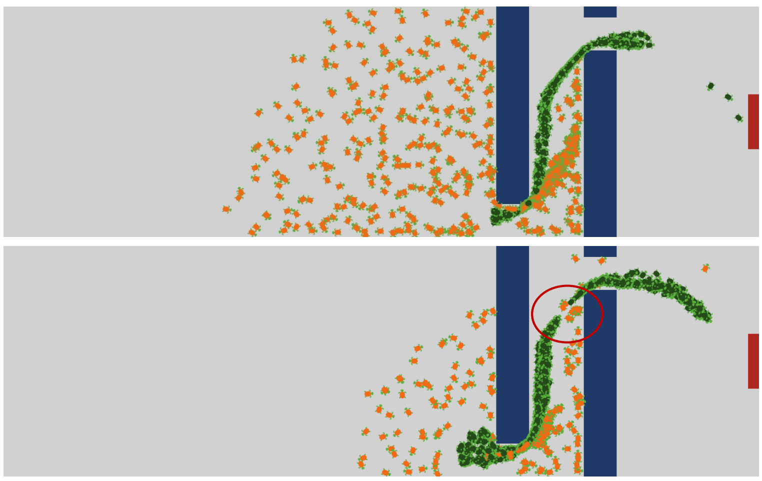

Figure 3 The model view of the evacuation process of BNE-SR combination.

However, this queue-induced deadlock is not permanent since the BNE agents were attempting to break free and navigate towards the relatively uncrowded area of the corridor, finding an alternative and potentially faster evacuation route. This also demonstrates the dynamic adaptability of the improved BNE model in addressing the immediate challenges during evacuations (i.e. blockades, bottlenecks, and congestions) as well as discovering efficient evacuation pathways.

4 Discussion and Conclusion

This paper proposed an improved pedestrian evacuation model employing Bayesian Nash Equilibrium (BNE) within an ABM approach, with the objective of producing forward-looking and realistic individual evacuating behaviours in complex environments. The BNE-informed model integrates a set of vertical blockades with adjustable gate widths to establish a simulation space with narrow corridor and bottlenecks, providing a further evaluation of the influences of BNE on individual navigation in complex space. The decision-making criterion of BNE evacuees was improved to a multi-strategy combination, in which 80% of evacuees take the best strategy, 15% make the second-best decision, and 5% choose the third-best one, to improve the evacuation efficiency. The preliminary results indicate that BNE plays a positive role in individual navigation in complex scenarios involving bottlenecks and blockades, reflecting on the distinct decrease of evacuation time with the increasing proportion of BNE-guided evacuees. The non-monotonicity of the variations in exit time also reveals the dynamic adaptability of the BNE model in addressing immediate challenges such as barriers, bottlenecks, and congestions, as well as discovering efficient route during evacuations.

However, a few limitations still need to be addressed: 1) The non-monotonicity of the evacuation time revealed that introducing an appropriate proportion of BNE evacuees into simulations has a significant influence on reducing exit time, which need to be further studied and observed at the individual level; 2) Different types of barriers should be introduced to further assess the feasibility of the improved ABM in other complex scenarios; 3) Apart from exit time, the model needs to be evaluated in the terms of other parameters (e.g. comfort level, etc.) to provide a comprehensive evaluation of the role of BNE played in individual navigation under complex situations; 4) Real-world scenarios need to be introduced to examine the simulation accuracy of the improved ABM. The above issues will be gradually solved in the next step of this ongoing research.

References

1 S. Bouzat and M. N. Kuperman. Game theory in models of pedestrian room evacuation. *Phys. Rev. E*, 89:032806, March 2014. doi:10.1103/PhysRevE.89.032806.

2 DongKai Fan and Ping Shi. Improvement of dijkstra's algorithm and its application in route planning. In *2010 seventh international conference on fuzzy systems and knowledge discovery*, volume 4, pages 1901–1904. IEEE, 2010.

3 Takashi Ui. Bayesian nash equilibrium and variational inequalities. *Journal of Mathematical Economics*, 63:139–146, 2016. doi:10.1016/j.jmateco.2016.02.004.

4 Yiyu Wang, Jiaqi Ge, and Alexis Comber. An agent-based simulation model of pedestrian evacuation based on bayesian nash equilibrium" (version 1.0.0). *CoMSES Computational Model Library*, 2022. doi:10.25937/75wf-aa82.

5 Yiyu Wang, Jiaqi Ge, and Alexis Comber. An agent-based simulation model of pedestrian evacuation based on bayesian nash equilibrium. *Journal of Artificial Societies and Social Simulation*, 26(3):6, 2023. doi:10.18564/jasss.5037.