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

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Abstract. This research presented an improved pedestrian evacuation Agent-Based Model (ABM) that employs Bayesian Nash Equilibrium (BNE) to simulate more representative and accurate individual evacuating behaviours in complex space. The improved model introduced a series of vertical barriers with adjustable gate widths, creating a simulation environment featuring narrow corridor and bottlenecks to evaluate the influences of BNE on individual navigation in complex scenarios. To better match with real-world evacuating behaviours, the decision-making criterion for BNE evacuees was refined to include a multi-strategy combination: with 80% of evacuees following the optimal strategy, 15% adapting the suboptimal strategy, and 5% taking the third-best one. The preliminary results highlight the positive influence of BNE on individual navigation within complex scenarios, as evidenced by a distinct reduction in evacuation time with the increasing proportion of BNE evacuees. The non-monotonic fluctuations in evacuation time also demonstrate the dynamic adaptability of BNE in addressing immediate obstacles (e.g. blockades and congestions) and discovering alternative and potentially faster routes during evacuations. This paper described the improved details of the proposed ABM followed by an analysis of experimental results. Several limitations were also identified.

Keywords: Agent-Based Modelling, Complex Environment, Pedestrian Evacuation, Bayesian Nash Equilibrium, Individual Navigation

1 Introduction

Our recent study proposed a novel ABM for pedestrian evacuation that incorporates Bayesian Nash Equilibrium (BNE) to address the absence of forward-looking individual behavioural models in related research on pedestrian evacuation simulations. This ABM has been demonstrated its ability to generate more intelligent individual evacuating behaviours in simple scenarios, as BNE-guided evacuees are capable to predict the future congestion levels to find faster evacuation routes. The results indicated that such model could better represent real-world evacuating behaviours and improve the effectiveness of emergency management strategies [4].

On this basis, the current research aims to further evaluate the impacts of the BNE model on individual navigation in complex space and its applicability in pedestrian simulations involving various scenarios. An improved BNE-informed ABM was developed by incorporating a set of vertical barriers with adjustable gate widths to create intricate evacuation environments. The underlying decision-making logic was also improved to better adapt to complex scenarios. A series of simulation experiments were conducted to assess the effects of improved model on evacuations in complex space.

2 An Improved BNE Behavioural Model

This research adopts a refined version of Bayesian Nash Equilibrium (BNE) as the underlying theory of individual decision-making in the improved ABM [1]. The refined BNE considers incomplete information, aligning more closely with the fact that some real-time information might be missed by pedestrians in real-world evacuation scenarios. The players in a BNE game can maximise their expected utilities and take the best strategy after considering the probability distribution of other players' next moves [1]. Consequently, the improved ABM accounts for the probabilities of neighbouring evacuees' next actions. Due to the non-sequential decision-making in BNE games, the BNE-guided evacuees in the model determined their future actions based on the values of total utility of their neighbouring patches [2].

The initial BNE model required all the evacuees to always select the patch with highest U_{total} to move, leading to the identical decisions in the latter stages of simulations, which in turn, resulted in localized congestions and lower moving speed [4]. This paper addressed the issue by refining the decision-making criterion of BNE evacuees through the introduction of a multi-strategy combination incorporating some stochasticity: with 80% of evacuees taking the optimal strategy (i.e the patch with highest U_{total}), 15% taking the suboptimal strategy (i.e the patch with second-highest U_{total}), and 5% choosing the third-best strategy (i.e the patch with third-highest U_{total}). To better match the demands for barrier avoidance, the candidate patch-set of BNE evacuees was improved from the patches ahead to all the passable patches on their Moore neighbourhood, to allow the evacuees to turn around and find an alternative evacuation route if there were some barriers or congestions in front (see Fig. 1).

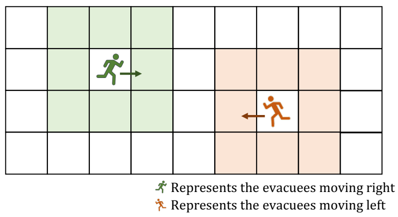

Fig. 1. Candidate patches of BNE-guided evacuees.

In addition to the improved BNE model, other two behavioural model, namely Shortest Route (SR) model and Random Follow (RF) model [4], were incorporated as control groups within the proposed ABM to provide a more comprehensive evaluation of the BNE model's influences on individual navigation in complex scenarios.

3 Model Analysis

3.1 Implementation Details

The initial version of the BNE-informed ABM and relevant experimental results were published on COMSES [3]. The improved version is still being developed and will be available once completed.

The main object of this research is to evaluate the performances of different behavioural models in individual evacuating behaviours, with a specific focus on the capability of BNE-guided evacuees to navigate in complex scenarios involving barriers, bottlenecks, and congestions. To achieve it, an evacuation space was established by incorporating narrow corridor formed by two vertical rectangular barriers with an adjustable-width gate for each barrier. The improved ABM was initialised with 2000 evacuees randomly scattering throughout the simulation space where was located at the left side of the vertical barriers. Two BNE combinations were provided which are BNE mixed with SR, and BNE mixed with RF. The mixing proportions could be changed to meet the requirements of simulations.

3.2 Result Analysis

Experiment Settings. To explore the influences of improved BNE model on individual navigation in complex space, this paper conducted a simulation study where the BNE evacuees mixed with those following one of the other two behavioural models (i.e. SR and RF). The percentage of BNE-guided evacuees varied from 0% to 100% at 2% intervals, and the gate width varied from 1 to 9 at 2-patch intervals. 10 replications were conducted for each parameter configuration and stopped once all the evacuees evacuate from the simulation space. The evacuation time of each simulation was recorded to assess the performances of the BNE model.

Experimental Results. Fig.2 illustrates the fluctuations in evacuation time of the evacuees following BNE-SR and BNE-RF combinations respectively in a complex scenario featuring blockades with varying gate widths. A local line of fit with 95% confidence interval was included in each plot to illustrate the relationships between the proportion of BNE evacuees, barrier sizes, and evacuation time. The results reveal few advantages of employing BNE when the gate widths of barriers were extremely narrow; however, a decreasing trend of evacuation time with increasing percentage of BNE evacuees is noticeable in the scenarios with wider gates. As shown, the positive influence of BNE on reducing exit time becomes salient with a rising proportion of BNE evacuees participating in the simulations.

The nonmonotonic variations in evacuation time against different BNE combinations in complex environments warrant further discussion. A reasonable explanation is that some of BNE evacuees may get trapped in the corner of corridors due to the queue of evacuees following SR or RF models during evacuations. SR-guided evacuees were observed to follow an identical path to avoid barriers and evacuate, potentially leading to a situation that BNE-guided evacuees were constrained within the corridor as SR evacuees were stuck at the bottlenecks casing congestions. However, BNE agents could bread free and navigate towards the uncrowded area, discovering an alternative and faster evacuation route. This also indicated the dynamic adaptability of BNE in addressing immediate challenges during evacuations and finding efficient evacuation routes.

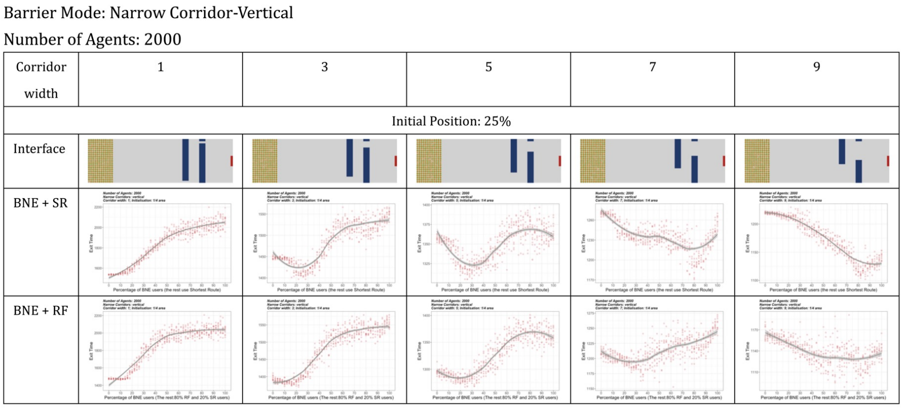

Fig. 2. Evacuation time against percentage of BNE-SR and BNE-RF combinations in complex scenarios with varied gate widths (2000 evacuees).

4 Limitations

Several limitations still need be addressed: 1) The non-linear fluctuations in evacuation time demonstrated the positive impact of introducing an appropriate ratio of BNE evacuees into simulations on reducing evacuation time, which need be further studied and observed at the individual level; 2) Different types of barriers need be incorporated to establish various complex scenarios, providing a comprehensive assessment of the improved ABM; 3) Apart from exit time, the proposed model requires further assessment in the terms of other parameters (e.g. average comfort level) to explore the roles of BNE played in individual navigation in various complex environments. The above challenges will be gradually addressed in the next step of this ongoing research.

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