An agent-based simulation model of pedestrian evacuation based on Bayesian Nash Equilibrium

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Model Description

A complete and detailed description of the initial model following ODD+D protocol (Müller et al. 2013) is provided in this section.

1 Overview

1.1 Purpose

The purpose of this model is to introduce a new individual decision-making method, BNE, into the ABM of pedestrian evacuation to properly simulate individual behaviours and movements. The model was built to balance between fast evacuation and high comfortability, which is a general conflict in the domain of pedestrian research. The interactions of pedestrians with their neighbours as well as surroundings was also considered in order to simulate a more realistic pedestrian evacuation. This model ultimately aims to explore the influences of BNE on pedestrian flows from various perspectives, especially pedestrian comfort and exit time in an emergency evacuation with different parameter configurations.

1.2 Entities, state variables and scales

The model contains two main types of entities: Patches (i.e. evacuation space) and Agents representing evacuating pedestrians. The variable names are same as the variables implemented in NetLogo.

The **Global Environment** is defined as model parameters at the system level, controlling all of the global variables representing the simulation environment. Its state variables are shown in Table 1.

Table 1. Global environment state variables

Variable Name	Variable Type and Units	Brief Description
number-persons	Person	Total number of agents in the model
Percentage-of-agents-with-BNE	Percent	The proportion of agents who are using BNE to evacuate
Probability-competing	Percent	The probability of agents entering one patch
door-width	Patch	The size of exits
move-speed	m/s	The speed when agents can move freely which reduces with the increasing crowd density
Step-length	m	The length of a single agent step
follow-radius	Patch	The distance that agents could see; it is used in Random Follow patterns
weight-Ud	Numeric	A coefficient to balance the influence of distance utility and expected comfort utility on determining agent movement directions.

Variable Name	Variable Type and Units	Brief Description
Moving-pattern	Chooser	4 patterns are available: Shortest Route (SR), Random Follow (RF), BNE mixed with SR, and BNE mixed with RF

Patches refer to the areas in the simulation space. The evacuation environment in this model was divided into 1360 (68*20) patches and as values of different utilities can control the directions of agents, these patch attributes are considered as state variables. Details of patch state variables are shown in Table 2.

Table 2. Patch state variables

Variable Name	Variable Type and Units	Brief Description
Uec	Numeric	Expected Comfort Utility
Ud_lt	Static; Numeric	Distance Utility, used by the agents moving to the left exit
Ud_rt	Static; Numeric	Distance Utility, used by the agents moving to the right exit
U_total	Numeric	Total Utility, the sum of distance utility and expected comfort utility
patch-target	Patch	Patches with maximum total utility

Agents represents the individual evacuees with different movement patterns and the related state variables are shown in Table 3.

Table 3. Agent state variables

Variable Name	Variable Type and Units	Brief Description
speed	m/s	The speed of each agent during evacuation
left?	True/False	Whether or not the agent moves to the left exit
follow?	True/False	Whether or not the agent follows another agents
door	Location	The location of exit that the agent chooses
BNE-type	Boolean	"1" – this agent uses BNE to evacuate; "0" – agent follows SR/RF patterns
nearby-leaders	Agentset	The optional neighbours when the agent want to choose one to follow; only used in RF patterns
leader	Agent	The neighbour followed by the agent

Scales. The spatial extent of this model is a rectangular region of 68 * 20 square patches (see Fig. 1). The model space is bounded and agents can only evacuate through the exits on either side. The model runs until all the agents evacuate from the simulation space. That is, the temporal scale in this model was not absolute and the number of time steps depends on the initial environmental conditions and the agents themselves. Three behavioural models were evaluated: Shortest Route (SR), Random Follow (RF) and BNE. The behavioural models were used to generate four moving patterns (i.e. model configurations): SR, RF, BNE mixed with SR, and BNE mixed with RF. The moving pattern are selected by the user at the beginning of the simulation.

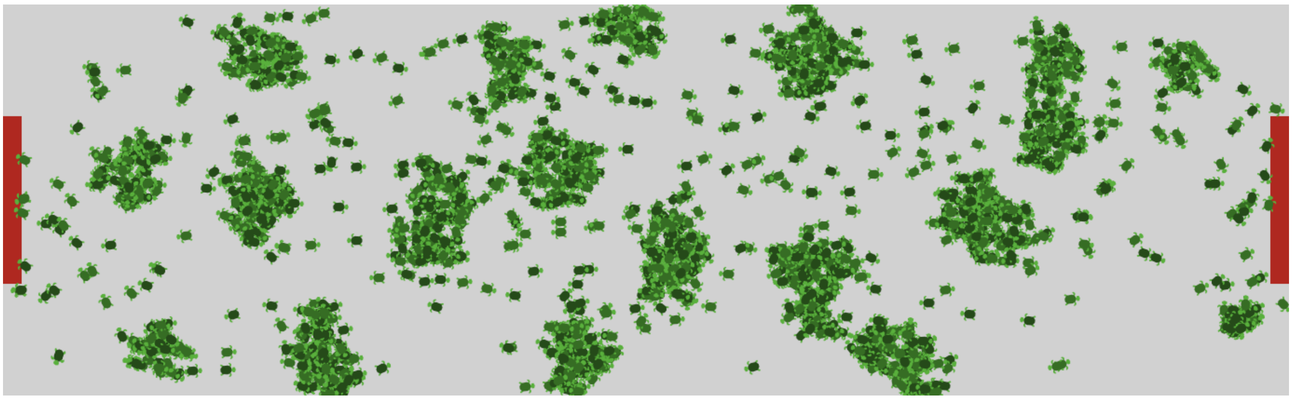

Figure 1. The interface of the simulation model, with agents in green and exits in red.

1.3 Progress Overview and Scheduling

The model simulates the complete process of pedestrian evacuation and demonstrates the detailed decision-making process of agents especially using BNE. Over each simulation run, patches and agents continuously update the relevant state variables in each time step.

The schedule of the model is shown as follows:

I. The simulation begins with a series of initial settings for global environment by the user, including the percentage of BNE agents, exit size, the number of agents, and other state variables. The type of moving pattern is also selected, with all the environmental attributes are static until the end of this run.

II. The patches execute the calculations of their distance utility and expected utility which are related to the implementation of BNE in the model. Expected comfort utility is continually updated until the end of simulation.

III. The agents choose a new direction (i.e. repeat their decision-making process) every time step in response to the new environmental conditions.

IV. The state variables, plots and model interface are updated.

2 Design Concept

2.1 Theoretical Background

Bayesian Nash Equilibrium (BNE) was used in the individual decision-making process of this model in order to augment the rationality of pedestrian evacuation simulation. BNE is an extension of Nash equilibrium and is a static game with incomplete information. It is generally defined as a strategy profile in which participants are assumed able to maximize their own expected utility based on the probability distributions of the strategies chosen by other players, and in this case, no player selects other strategies (Ui 2016). That is, the primary element of individual decision-making is the probability distributions of strategies played by other nearby participants, especially the probabilities of neighbours choosing the same strategy as the player. In this model, this is reflected as the probability distributions of the next actions of nearby agents and a series of utility calculations for candidate patches. The relevant underlying equations are described below.

2.2 Individual Decision-making

Decision-making is modelled on an agent level in this research. In this model, the decision-making processes of agents are different based on the three behavioural models (i.e. SR, RF and BNE). For BNE agents, they tend to move to a neighbour patch with maximum total utility every time step, which depends on the probabilities of nearby agents' next action and the surrounding environment. Each agent using RF follows a neighbour in sight at random and repeats this selection process until the end of simulation. Agents using SR makes only one decision (i.e. which exit to move towards) at the beginning of the simulation, which means that their directions remain unchanged until they succeed in evacuating from the simulation space.

2.3 Individual Sensing

Agents following the RF pattern are assumed able to sense their neighbours within a specific radius of their current locations. The value of this radius remains constant during simulation and could be adjusted by the corresponding slider "follow-radius". Agents followed BNE pattern are assumed to be able to sense surrounding conditions and select the target from nearby patches to move in each time step. Specifically, an agent using BNE can sense and potentially move to all neighbouring patches which are located between its current patch and the exit. The choice criteria is the total value of distance utility and expected comfort utility of each patch.

2.4 Individual Prediction

Individuals in this model use the information on neighbours' current location and the probability distribution of their moving directions to predict future situations. Specifically, expected comfort utility of neighbouring patches is estimated over a time step by using the explicit prediction of nearby agents $p(n)$ and comfort coefficient of each patch $U_c(n)$.

2.5 Interaction

Interactions among agents are mediated through the variations of expected comfort utilities of neighbour patches. In BNE patterns, each patch's expected comfort utility depends on the expected number of agents who will be on the patch in the next step, which in turn determines the number of agents in the nearby patches. Then, each agent will determine its direction by comparing the total utilities of six patches which are within its optional directions (i.e. candidate patches P_0, P_1, …, P_5) (details in Section 3.4). That is, the current position and expected next move of agents influence the expected comfort utility of patches, which, in turn, affects the next move of nearby agents.

2.6 Heterogeneity

Agents are heterogeneous in their decision-making process based on their own behavioural type. For agents following the Shortest Route pattern, their only decision is to move to the exit; For those with the Random Follow pattern, agents need to choose a neighbour in their view each time step and repeat this process until the end of simulation; For those with BNE pattern, agents select the patch with maximum total utility to move to and repeat this decision-making procedure every time step until they evacuate successfully.

2.7 Stochasticity

Stochasticity is introduced in two ways in this model. Firstly, the model is initialized randomly based on the settings configured by the user. Specifically, (a) the location of agents, (b) the random allocation of behavioural type, and (c) the initial directions of agents are considered to be stochastic at the beginning of a simulation. Secondly, when an agent following the RF pattern determines where to move, its choice of its following target is partly stochastic as it is limited by its view and the exit selected. Similarly, when two patches have same and maximum value of total utility, the agent in BNE pattern will randomly select one to move to. This decision is stochastic but not completely random since the choice is restricted by the location and direction of agents.

2.8 Observation

The purpose of this model is to explore whether and how BNE affects pedestrian evacuation procedures in the case of emergency, with two main measurements: evacuation time and pedestrian comfort level. The exit time and average expected comfort utility of each run are collected at the end of simulation in order to compare evacuations with varying proportions of agents following the BNE pattern in the simulation.

3 Details

3.1 Implementation Details

The initial model was developed in NetLogo 6.2.2.

3.2 Initialization

The initial state of the model is a hypothetical evacuation space with emergency exits located on either side. The agents are initialized by setting the total number of persons (i.e. number-persons global parameter) and the percentage of BNE users through a slider *Percentage-of-agents-with-BNE*. The agents are randomly scattered over the simulation environment. The initial speed of each agent is tailored according to the number of agents on its nine neighbouring patches, and all the adjustments are based on the reference speed assigned by the global parameter move-speed. The agent moving patterns are selected through the moving-pattern. The moving patterns in this model consist of Random Follow (RF), Shortest Route (SR), BNE mixed with RF, and BNE mixed with SR. For the first two patterns, all the agents are set to same moving pattern during simulation. For the last two patterns, a specific proportion of agents use BNE to evacuate which is defined by the global parameter Percentage-of-agents-with-BNE, and the rest follow one of two other patterns (i.e. SR or RF) based on the selected option.

Each patch calculates its own distance utility and expected comfort utility at the initialization stage. BNE agents compare the value of total utility (i.e. the sum of U_d and U_{ec}) for the candidate patches and select the one with maximum value to move in each time period. That is, the patch attributes are being continuously updating every time step to provide undated information to agents using BNE for determining their next actions. At present, a series of global parameters (e.g. door-width, follow-radius, etc.) are fixed due to the main research focus, which is the exploration of whether and how BNE affects pedestrian emergency evacuation, but variations in these global parameters could be evaluated in further research.

3.3 Input data

So far, no input is read in this initial model.

3.4 BNE

In order to translate the rationality of BNE theory into specific decision-making rules, a series of utility functions are introduced in this model to realize the BNE behavioural model. Individual decision-making depends on the value of "Total Utility" for optional patches. Total utility consists of three main elements: Distance Utility (U_d), Comfort Utility (U_c) and Expected Comfort Utility (U_{ec}), and refers to the total value of U_d and U_{ec}. Specifically, the decision made by each BNE agent considers the distance from its current position to the exit, the number of neighbours who may move to the same patch as itself, and the possible surrounding situations in the next time step. Then, the patch with maximum total utility (i.e. the sum of U_{ec} and U_d) is selected by the agent to move to. In other words, agents use BNE to predict the congestion level in next time step and then avoid the most clogged patches during their movement, in order to determine an evacuation route with less exit time and higher comfort level. The choice criteria is the value of total utility in neighbouring patches, which is evaluated by agents to decide where to go. In this model, all BNE related utilities were set as patch attributes and are described in detail below.

A. Distance Utility.

This represents the distance from the current location to the exit. Since we assume that agents tends to choose the patch with largest value of total utility, U_d should be set to an increasing attribute value with it gets closer to the exits. Due to two exits existing in the evacuation space, two sets of distance utility are determined for the agents moving to the right or left exit respectively (i.e. parameters U_{d_rt} and U_{d_lt}). The equation is:

$$U_d = \frac{D - d}{D} \tag{1}$$

where, d represents the distance from current patch to the exit, and D refers to the diagonal of the evacuation space.

B. Comfort Utility.

Comfort Utility, U_c is a set of coefficients that form a crucial component of Expected Comfort Utility, reflecting the comfort level of agents in one patch. According to the speed-density relation associated with the Spatial-Grid Evacuation Model (SGEM) (Lo et al. 2004), the value is set to 1 when two or less than two agents occupy the patch. It decreases as the number of agents on the patch increases, by setting the value to be a proportion of the free-moving speed (i.e. 1.4 m/s) relative to the number of agents on the patch. Considering the limited space capacity in reality, U_c stays at zero when more than 4 persons move to the same patch. The equation is as follows, with full details in the calibration section (Section 3.1):

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

where, n represents the number of agents in one patch.

C. Expected Comfort Utility.

According to the definition of BNE, individual decision-making in this model is independent, which means that no account is taken of the agent's previous actions in each time step. The main factors determining where agents go is the number of agents who may move to the candidate patches in next time step. In other words, the probability of the neighbours' next actions has an impact on the decision-making process of the agent.

It is assumed that the probability of reverse movement during evacuation is extremely low, which means that each agent has six optional directions (i.e. candidate patches) $P_0, P_1, \ldots, P_5$ in each time step (see Fig. 2). The probability of entering these candidate patches Pm is set to the same value (i.e. 16.7%) by default, which could be adjusted using the Probability-competing slider in further studies.

Thus, the patch variable named Expected Comfort Utility (U_{ec}) for each patch is dynamic in this model and reflects the interaction between agents. It is defined as the multiplication of comfort utility U_c and the probability $p(n)$ that a certain number of agents move to this patch in next time step (see Eq(3)):

$$\begin{aligned} U_{ec} &= \sum_{n=0}^{4} p(n)\, U_c(n) \\ &= \sum_{n=0}^{4} C_N^n\, P_m^n (1 - P_m)^{N-n} U_c(n) \end{aligned} \tag{3}$$

where, n represents the number of agents in this patch; and P_m refers to the probability of agents entering the candidate patches, which is set to 16.7% by default. In this way, the calculation of U_{ec} takes into account the agents on both the patch and its nine neighbouring patches.

The relationships of these utilities are illustrated as Fig. 3.

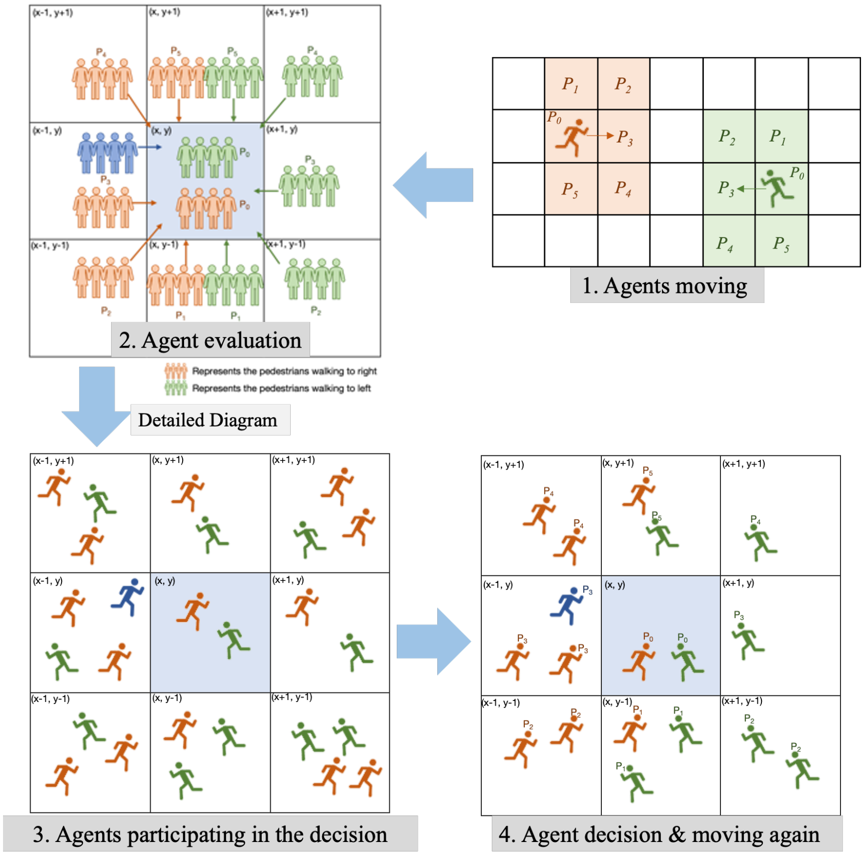

Figure 2. The scheme of agents' decision-making

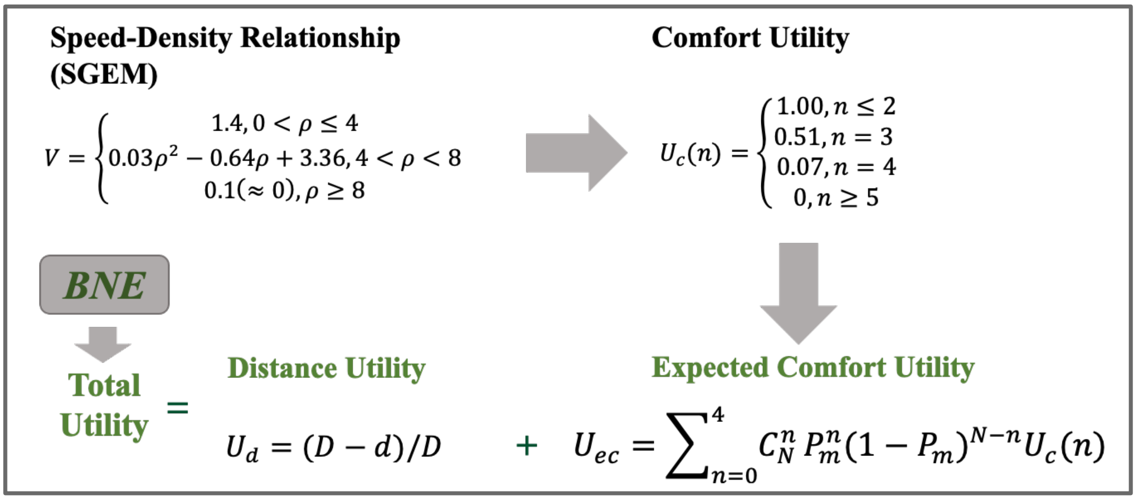

Figure 3. The schema of BNE utilities

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