

Overlap-avoiding Tickmodel: an Agent- and GIS-Based Method for Evacuation Simulations

Ervin Wirth^{1*}, György Szabó¹

RESEARCH ARTICLE

Received 30 March 2017; Revised 16 May 2017; Accepted 18 May 2017

Abstract

Evacuation simulation is a method to determine evacuation times for areas, buildings, or vessels. It is based on the simulation of crowd dynamics and pedestrian motion; in this paper, we investigated the evacuation characteristics with a new motion model. The motion model and modeling space were implemented in an agent-based environment. The model is simple and generally applicable, it navigates the agent towards the destinations (safe zones) in a mixed macro-micro approach. The simulations were tested in a geospatially modeled lecture hall of the Budapest University of Technology and Economics (BME). The evacuation times and the panic rate were both estimated; a new way of measurement was applied for panic. Finally, conclusions were made on the person count ~ evacuation time and person count ~ panic rate relations. The paper introduces the key factors of this complex modeling phenomenon and demonstrates how to set up an agent-based evacuation model. The results can simulate the real phenomenon and constitute valuable assets for decision-making in public safety issues (architectural design, evacuation protocol, regulations of space).

Keywords

general, evacuation model, ABM, GIS, risk management

1 Introduction

Evacuation simulation is a method to determine evacuation factors (times, panic, mixture) for spatial objects (halls, buildings, public places, vessels). It is based on the simulation of crowd dynamics and pedestrian motion. This complex phenomenon can be easily described by an agent-based model, which provides a natural description of a system in general.

The term agent-based modeling (ABM) refers to the use of computational methods to study dynamic processes of interacting agents. ABM models seek macro-level understanding of micro-level simulations. They generally involve bottom-up, rather than top-down modeling [1].

The agents can be linked to each other, or can relate to the static part - the raster world - of the system. In this context the expression “world” can refer to any spatial entity like a building, lecture hall, land use, landscape, or it could be an empty space as well.

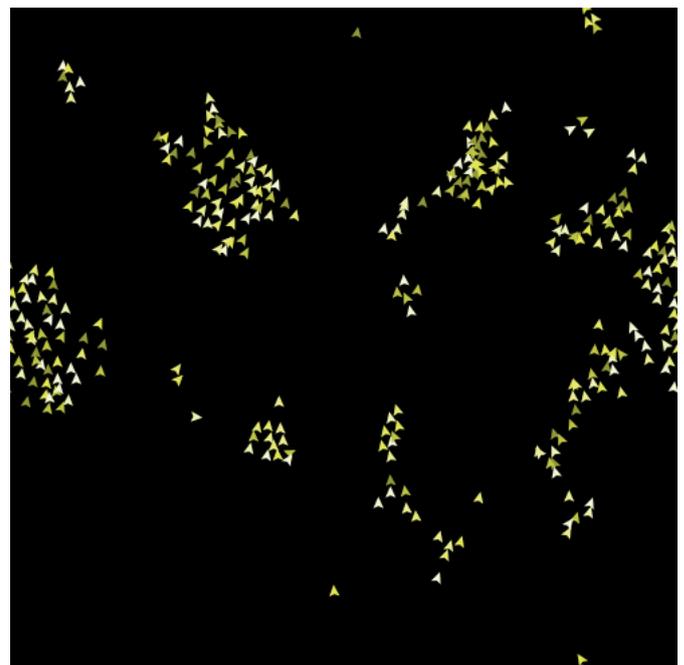


Fig. 1 Flocking birds in NetLogo [2] agent-based modeling environment in an empty torus world (wrapped in x and y directions) [3].

¹Department of Photogrammetry and Geoinformatics,
Faculty of Civil Engineering,
Budapest University of Technology and Economics,
H-1111 Budapest, Hungary

*Corresponding author email: wirth.ervin@epito.bme.hu

The three principal advantages of agent-based approach over the traditional top-down modeling are as follows:

- dynamically capturing emergent phenomena;
- provides a natural environment for study, which is closer to the reality than that of other modeling approaches;
- it is flexible, particularly in relation to geospatial models.

The agent-based models can be categorized to two groups according to utility: explanatory and predictive models. The explanatory modeling approach tries to explore theory and generate hypotheses. This kind of model generally focuses on a specific aspect of a system, putting emphasis on some details of a phenomenon and ignoring others. The other model category is the predictive model, which is designed to simulate real-world systems, and useful for scenario development and policy decision [1].

Real-life experiments on evacuation are costly in practice, which encourages researchers to simulate evacuation behavior using various modeling approaches [4]. Various methods from different disciplines have been used to simulate evacuations: particle-swarm-optimization [4], social force model [5], and agent-based grid models as well.

Our 'GIS-ABM' combined model can be used for any geo-referenced object representation. It is sophisticated, since the artificial people (agents) are modeled as circular areal features, in contrast to the commonly used rectangle grid-models (1 cell = 1 person). This kind of geometric implementation involves finer raster resolution, which needs different spatial relations. Instead of simple rectangular room models, our model handles all kind of spaces (including empty spaces, obstacles). The method is general, so it does not need the customization of space, or any evacuation semantics or order to control the flow. It uses one raster for global (macro) navigation, which is the walking cost layer that is easily obtainable through a GIS (Geographical Information System) software. This cost layer can consider elevation or friction. For local (micro) navigation the overlap-avoiding method was used, which will be introduced in later sections. A beam scanning code was also implemented to exclude spaces behind obstacles. The local navigation model contains the agents' logic, their goal is to escape from the lecture hall as quickly as possible. Their movements are controlled synchronously by a simple rule: look around, find the lowest cost evacuation route, and try to progress in that way.

We would like to highlight the basic characters of our model after Gershensfeld's classification [6]:

- specific – general
- model estimation – first principles model
- numerical – analytical
- stochastic – deterministic
- microscopic – macroscopic
- discrete – continuous
- qualitative – quantitative

2 Geometric modeling

As the venue of the simulation a lecture hall was selected, which is located in the main building of the Budapest University of Technology and Economics. The hall consists of 14 rows with 16 seats in each, this means 224 seats in total.



Fig. 2 The test lecture hall

There are two aisles on the sides, which end in two doors, and another corridor between the last row and the wall.

Despite the advantages of ABM, it has not been widely adopted in geospatial research, even though there is no obvious reason for this [1]. In this paper, we chose NetLogo agent-based modeling software for simulating evacuation, like other researchers did as well [7, 8].

Generally, they created cellular automaton like models, where one patch (or cell) is equal to one person, and the relations are based on cellular neighborhood models such as von Neumann and Moore [7, 8]. Crooks et al. used 37.5 cm by 37.5 cm size cells for an agent [7]. Instead of the 'one agent per cell' strategy our fine resolution model can handle smaller space units (10 cm by 10 cm), where the agents spread more cells.

In order to analyze the agents' behavior first an artificial world has to be created by the following steps:

1. A CAD or BIM model of the hall has to be either created or obtained that represents exact measurements.
2. The drawing then should be converted to a GIS model (which can be georeferencing and digitizing), where attribute data can be added. At this step, CAD lines have to be converted to areas or faces which can be characterized by location identifiers.
3. The agent-based environment's prior modeling space is the raster world (more advantageous for fast calculations). For this reason, the GIS vector model has to be rasterized.
4. Another raster map has to be created with the same extensions and resolution, which shows the anisotropic cumulative cost of moving between the exit locations (doors) and the cells of the hall. This layer is used for macro level indoor navigation. This raster map can be created by GIS functions like `r.walk` in GRASS [9].
5. The derived raster layers (walking costs, location identifiers) can be loaded and overlaid in the agent-based modeling environment or simulation framework.

6. Finally, the agent-based model has to be called repeatedly on parallel computing threads in a statistical software to investigate the behavior space. We used R at this step. [10]

The general method can be extended using more walking cost layers, which refer to different building exits. Then these layers can be combined, and different evacuation plans (walking cost layers) can be assigned even to adjacent persons.

The construction of the evacuation simulation model started with creating the plan of selected lecture hall, which was georeferenced to a TMS (Tile Map Server) layer.

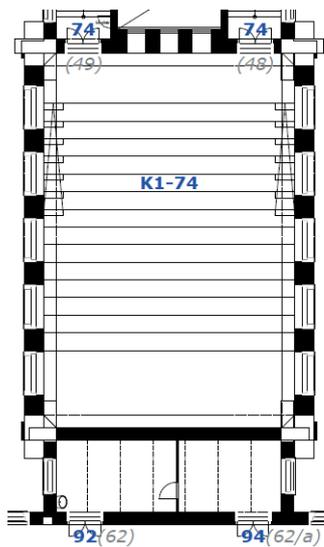


Fig. 3 The plan of the hall

For the geoinformatics tasks of the project, QGIS 2.14 was used [11]. The georeferencing process covers the adjustments of raster – rotation, translation etc. – to fit into a well-defined coordinate reference system, which known by the ABM software as well. Then the points were sketched up with CadTools [12], which is a QGIS plugin. After creating the GIS model, we had to decompose the hall to elements, and identify their unique parts.

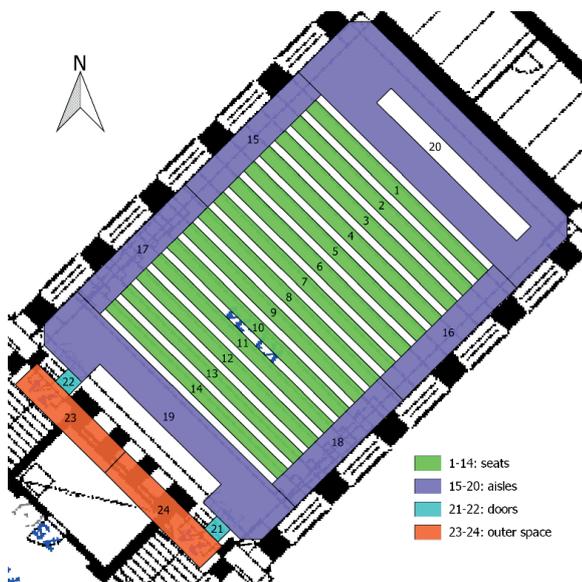


Fig. 4 The decomposition of the hall. By the identifiers the student can be placed in any row of the simulation hall.

3 Installation parameters

The simulations were performed on a grid data model, what we can obtain through rasterization process as written in Section 2 – Geometric modeling. The cell (called ‘patch’ in ABM) size (i.e. length of its side) was chosen to 0.1 m. The students’ diameters were set between 36–52 cm uniformly after US and British shoulder breadth (bideltoïd) samples in the age of 18–65 [13].

We tested 4 setup variations of the hall: in the first and default setup, both doors were open, but only with one leaf (see doors in Figure 3.). In this case, the width of the doors was 75 cm. The second was the ‘two doors two leaves’ version. If both leaves are open then the width is 150 cm; in the case of 2 doors the total exit width is 3 meters. The third and fourth setups were the mentioned leaf options (open/half-open) with only one door. Since the hall is symmetric, the door selection (left or right) is irrelevant. The raster models were resampled with all the variations to serve as simulation base layer.

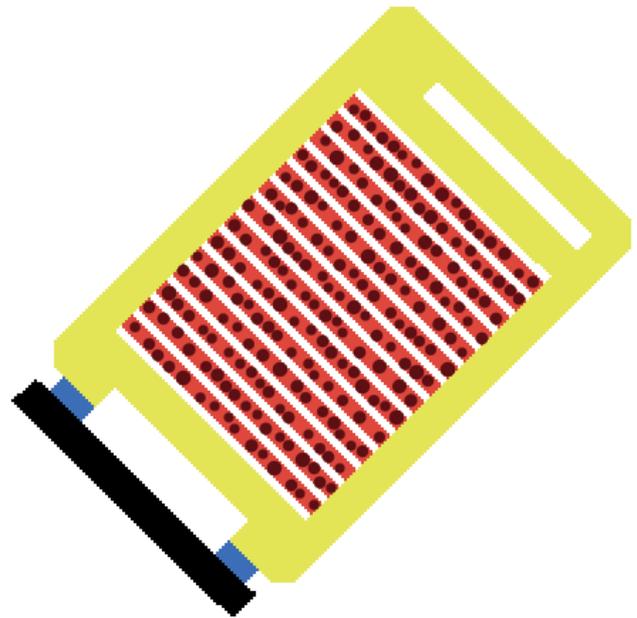


Fig. 5 The hall (2 doors with 2 leaves open) with 220 students in an ABM environment. Red: benches; yellow: aisles/corridors; blue: doors.

In the space colonization process, the students were dropped down randomly in the seat lines, until a given count was reached. If there was an overlap, the agent was eliminated and a new position was tried.

4 Agents’ movement model

Neighborhoods can be specified using a variety of mechanisms. Agent interactions can easily be controlled by networks based upon space. In our case, the agents’ movements are mainly influenced by the walking cost layer (described in Section 2 – Geometric modeling). This layer aims the macro-level orientation of the agents.

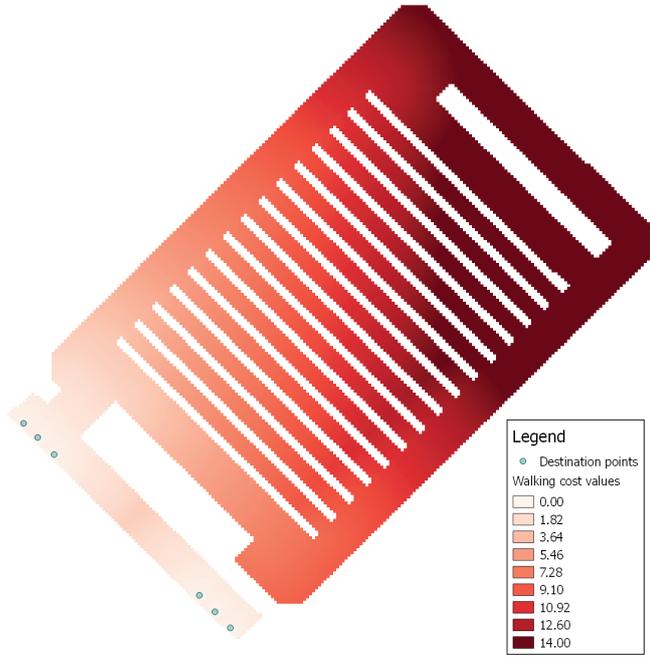


Fig. 6 Anisotropic cumulative walking cost map in the case of one open door with two leaves. Darker color represents higher cost. Two null rasters were used for input friction cost and elevation parameters. Consequently, elevation can be considered during the path optimization.

The agents apply a simple rule, they try to move to a patch with lower cost than that of the patch they are standing. First, all the agents query the patches around in a step-size buffer. Then they collect the nearby agents with a larger radius of searching circle. The number of the initially visible patches around is reduced by the number of ones located in the buffers of mobile (neighboring persons) and immobile obstacles (walls, benches). These buffer sizes depend on the self-size (radius) of the agents, and the sizes of the nearby persons. After the reductions, we got the possible patches to step (Fig. 8. and Fig. 9.).

For mathematical description, first we define the sets, where A contains the agents, and P the patches:

$$\begin{aligned} A &= \{ \text{All agents} \}, P = \{ \text{All patches} \} \\ W &= \{ P \mid \text{cost}(P) \neq 9999 \} \\ O &= \{ P \mid \text{cost}(P) = 9999 \} \\ P &= W \cup O \end{aligned}$$

where W : walkable patches, O : obstacle patches
 $\forall i \in A$

$$p(t, i) = \{x, y\}$$

where function p gives the position of a particular agent i in epoch t .

$$R = \left\{ w \in W \mid (w_x - p(t, i)_x)^2 + (w_y - p(t, i)_y)^2 \leq s^2 \right\}$$

where w denotes a walkable patch, s is the step size of the agent, and R refers to those patches the agent i can step.

$$r(i) = 18 \dots 26 \text{cm}$$

$$N = \left\{ j \in A \setminus \{i\} \mid (p(t, j)_x - p(t, i)_x)^2 + (p(t, j)_y - p(t, i)_y)^2 \leq (s + r(i) + (\max_{i \in A} r(i)))^2 \right\}$$

where N is an agent subset, which contains the neighboring agents. And r are the radii of the agents.

$$NB = \bigcup_{\forall n \in N} \left\{ w \in W \mid (w_x - p(t, n)_x)^2 + (w_y - p(t, n)_y)^2 \leq (r(i) + r(n))^2 \right\}$$

where NB is the avoid-buffer patch set of the N persons. The corresponding code snippet from NetLogo can be seen in footnote.¹

$$M = \left\{ o \in O \mid (o_x - p(t, i)_x)^2 + (o_y - p(t, i)_y)^2 \leq (s + r(i))^2 \right\}$$

M contains the close obstacle patches of agent i . Then the agent- i -sized buffer of the immobile obstacles (wall, benches) has to be created:

$$OB = \bigcup_{\forall m \in M} \left\{ w \in W \mid (w_x - m_x)^2 + (w_y - m_y)^2 \leq r(i)^2 \right\}$$

Afterwards, the buffer of the agent i must be calculated:

$$IB = \left\{ w \in W \mid (w_x - p(t, i)_x)^2 + (w_y - p(t, i)_y)^2 \leq r(i)^2 \right\}$$

And finally, we got the set of potential patches to step:

$$S = R \setminus (NB \cup OB \cup IB)$$

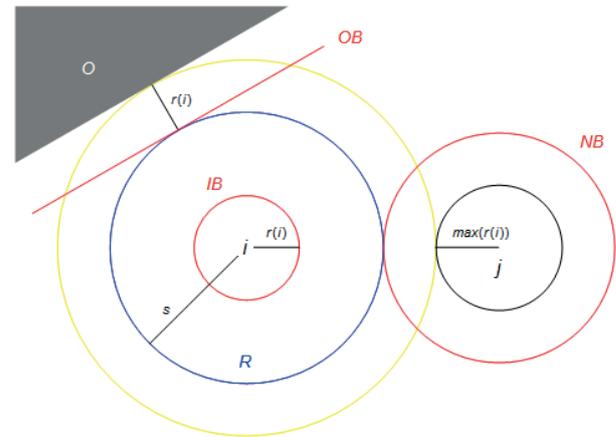


Fig. 7 A non-overlapping boundary case. The agent can step anywhere within the blue circle. The yellow circle is the searching circle for obstacles.

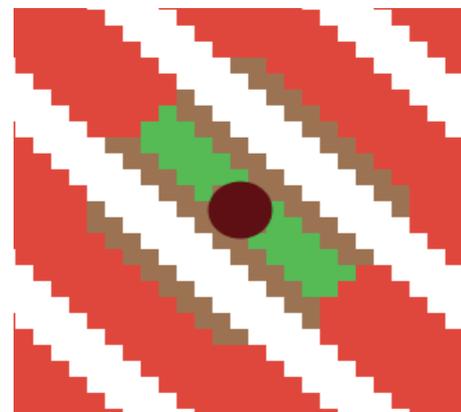


Fig. 8 A person on the seat, initial state:
 brown patches – reserved patches by obstacles and itself
 green patches – potential patches to step

¹ ask close-persons [set reserved-patches (patch-set reserved-patches patches in-radius-nowrap (asize + mysize) with [cost != 9999])]

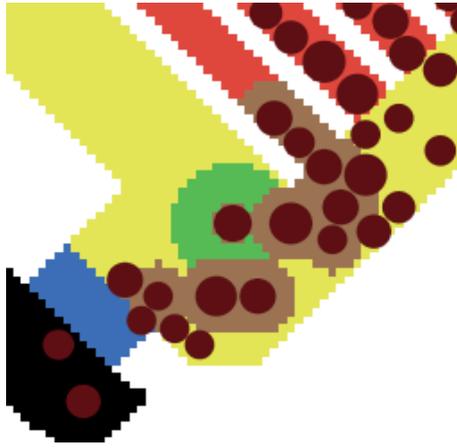


Fig. 9 A more complex situation with an agent on the way (from 220 agents):
brown patches – reserved patches;
green patches – potential patches to step.

Finally, if there are patches available for the agents to step on with lower potential cost than the one it's standing on, it will step on the one with the lowest cost. The step-size of the persons was chosen to 7 patches long identically. That means 70 cm according to the resolution, which is close to the reality [14]. We have to notice that a line of sight analysis was also implemented in the model, which can reduce the patches of the initial R set. This analysis could be relevant in the case of larger step sizes, or with smaller obstacle elements. The method wasn't drew up mathematically, but it can be found in the shared source code.

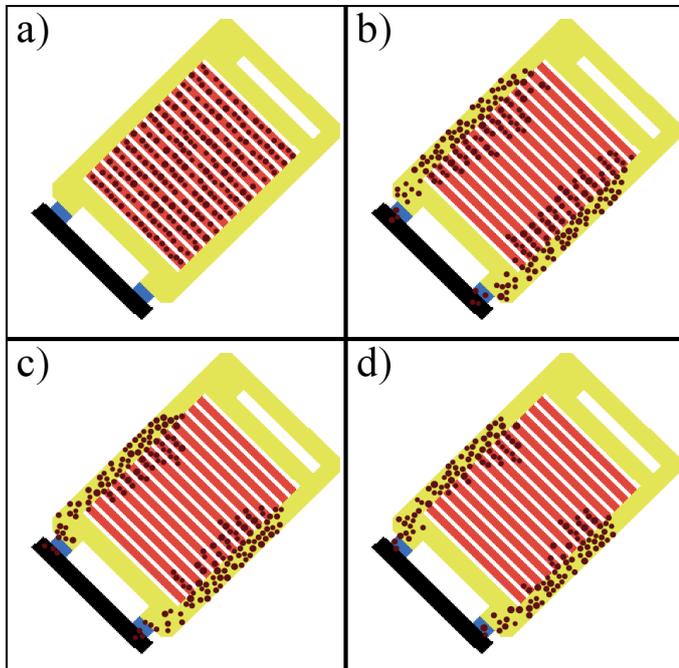


Fig. 10 The simulation epochs of the evacuation of 220 people:
a) initial state, b) the agents' positions after 10 ticks, c) 20 ticks, d) 30 ticks.

In Figure 10 can be seen that the first rows will become empty first. However, persons from them won't be the first ones to leave the hall, but not the last either.

The method shows similar movement characters – arching and clogging – like the Helbing-Molnár-Farkas-Vicsek (HMFV) social force model [5] without the implementation of physics. It shows more irregular, life-like patterns in the queuing, instead of the regular, circular pattern [5].

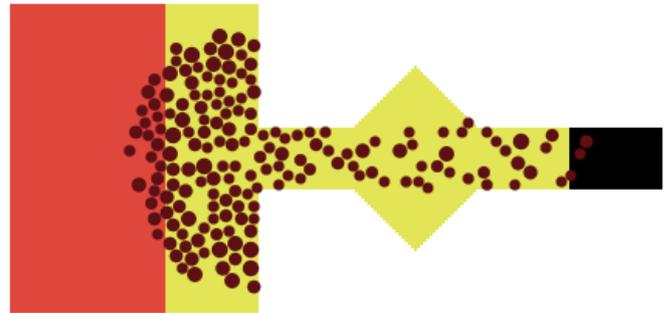


Fig. 11 Observed simulation patterns in motion: arching and clogging.

5 Model properties

Summing up the advantages and characteristics of the proposed combined ABM/GIS evacuation method:

- emphasis spatial aspects, based on overlap avoidance
- geometry-based model with few parameters
- fine raster resolution (e.g. 0.1 m)
- sophisticated agent model (dealing with different agent sizes and applying round shape)
- robust navigation: the walking cost layer does not lead to dead ends
- using micro orientation, which considers obstacles and other persons
- handles all kinds of space (including gaps, obstacles), instead of experimental rectangular spaces [5, 8]
- does not need the customization of space, any evacuation semantics like way-points or order to control the flow
- deterministic character: the results only depend on initial conditions: agents' position, orientation and size; space setup
- human motion patterns: clogging and arching
- scalable, can be expanded easily (e.g. different step-sizes following some distribution)
- 2+1D method: elevation can be considered in the walking cost layer
- could be implementable for 3D modeling by cubic cells (3D walking cost layer and world)

Since it solves all the anomalous cases, we propose our method as a general implementation to carry out simulation on the real building models (CAD, GIS, BIM).

6 Simulation outcomes: time

As the base of the simulation, the agent step was selected. There is a special simulation metric called 'tick'. Every tick forces the agent to step one if it is possible.

In order to draw conclusions, the simulations were replicated 20 times by each parameter setup. We increased the number of persons by 30 in each setup till reaching the maximum 220 capacity of the hall. That means 8 (person count) * 4 (door setup) * 20 (repetition); in total 640 realizations.

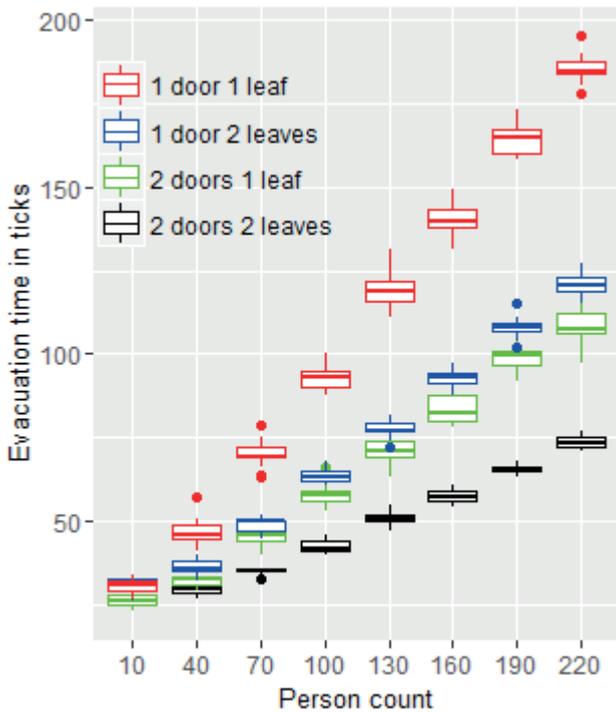


Fig. 12 Boxplot of evacuation times (in ticks) in function of person count. The simulation stops if all the persons got out of the lecture hall. Wider rectangles indicate higher variation in results.

On the boxplot, we can see that all the evacuation times seem to follow a linear trend, especially after the panic appears (at 70 persons' setup in Fig. 13.). This linearity could be due to the fixed passing capacities of the doors. Similar linearity trends were detected in evacuation time and person count connection by Izquierdo et al. [4]. They used 'critical zone' for larger number of people, where the quadratic trend in evacuation transformed to linear. We would like to highlight that this 'critical zone' is more dependent on the persons' interactions (panic), which comes from the number of the persons, and character of the space as well. In the case of two open leaves (even in one door) lower variance can be seen in the results since the use of wider exits (instead of the summed exit width) implies more stable or accurate evacuation times. But we can reach faster evacuations by the proper division of the doors on the aisles' axes because evacuations times are lower in case of '2 doors 1 leaf' (2*75 cm) than that of the '1 door 2 leaves' (1*150 cm) setup. Generally, we can conclude that, the variance (and variation, deviation) of evacuations times does not depend on the door setups, but wider doors implies smaller deviations. After the critical zone (70 persons), in Fig. 12. the green and red rectangles are wider (1 leaf), the black and blue are narrower (2 leaves).

A brief information product can be created to the halls by the division of simulation results.

Table 1 Evacuation time factors normalised to 130 persons, 2 doors with 1 leaf setup

Person count	2 doors with 2 leaves	2 doors with 1 leaf	1 door with 2 leaves	1 door with 1 leaf
10	0.36	0.36	0.43	0.43
40	0.41	0.45	0.51	0.65
70	0.49	0.63	0.68	0.98
100	0.6	0.81	0.88	1.3
130	0.71	1	1.08	1.66
160	0.8	1.17	1.29	1.95
190	0.91	1.38	1.5	2.29
220	1.02	1.52	1.68	2.58

The created table provides useful information for emergency regulations. This kind of table can be created to all the lecture halls of the university, or rooms of other public buildings.

7 Simulation outcomes: panic

During the simulations, a waiting-time property was also registered. It was a counter for each agent, which stands on 0 till the agent could step. Otherwise, it started to count over that epochs the agent was not able to move. If there was a place to step, the counter was reset to zero. This way of panic measurements is connected to these waiting times; we queried the waiting times in each epoch for all the agents and summed them.

$$w(i,t) = \begin{cases} w(i,t-1) + 1, & \text{if } \nexists \text{ potential patch to step} \\ 0, & \text{if } \exists \text{ potential patch to step} \end{cases}$$

where i is the identifier of the agents, t means an epoch of the simulation, and w is the function for waiting times.

Thus, we can analyze exact moments when the waiting time sum was high or low. Finally, we integrated the waiting times by the evacuation to get the panic rate. Then total panic rate (PR) was normalized with the person count variable to reach an objective measure:

$$PR(a,d) = \frac{\sum_{t=1}^d \sum_{i=1}^a w(i,t)}{a}$$

where a is the number of the evacuating persons, and d is the duration of the evacuation.

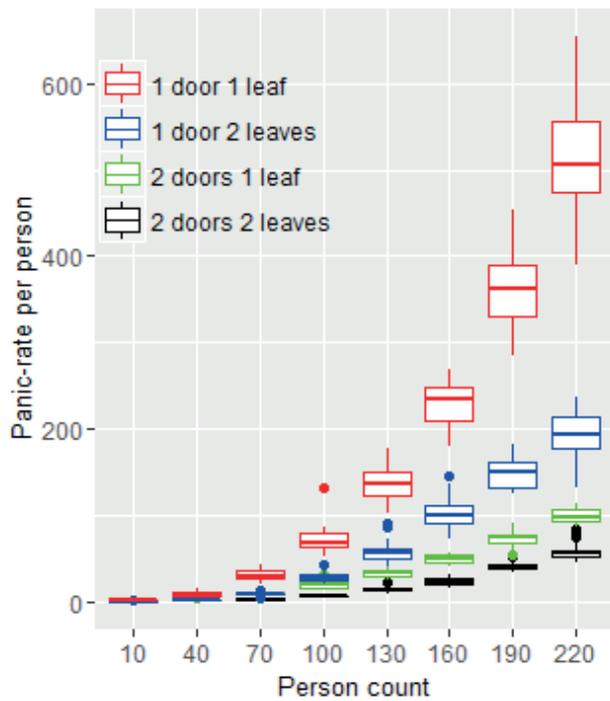


Fig. 13 The boxplot of panic rate-person relation. Based on 20 samples on each setup; in total 640 realizations.

As it can be seen in Figure 13, the panic follows a non-linear trend. It starts to appear at the 70-person setup, and then it increases exponentially with increasing variability. The highest panic-rate per person values comes with the highest number of students. Like the person-time boxplot, the orders of setups are the same, but we can see that there is a bigger gap between the ‘1 door 2 leaves’ and ‘2 doors 1 leaf’ setups, while there is only a smaller gap between the ‘2 doors 1 leaf’ and ‘2 doors 2 leaves’ setup.

8 Space optimization analysis

In this section, we studied the evacuation results in the function of different student distributions in the seats. The first two options were the ‘every second bench’ scenarios (Fig. 14a and 14b), then comes the random distribution setup (Fig. 14c), and finally the rear benches were filled (Fig. 14d). All the scenarios were repeated 20 times with 110 students.

The rear setup (d) is the fastest but comes with a little more panic. Setup c – homogenous distribution – shows less contact (measured as panic) with an average evacuation time. Consequently, we can state that the distributions of the students is not relevant, the evacuation time depends on the closeness of the student’s centroid to the doors, and the panic stems from the compactness.

In this last section, we monitored the mixing of the crowd by registering the identifiers of the benches to the agents. Here we present similar plots to Viswanathan et al. [15], who used zoned evacuation times as well. Viswanathan et al. created evacuation density plots come from different sized (5, 10 m) buffer rings around the exit. They used a rectangular room in their simulation, which cannot adapt in a complex space, like the introduced hall. Therefore, we implemented it for the benches as identical spatial structures. The result of 220 students’ evacuation through 2 doors with 2 open leaves can be seen in Fig. 15., where we repeated the simulation algorithm 40 times.

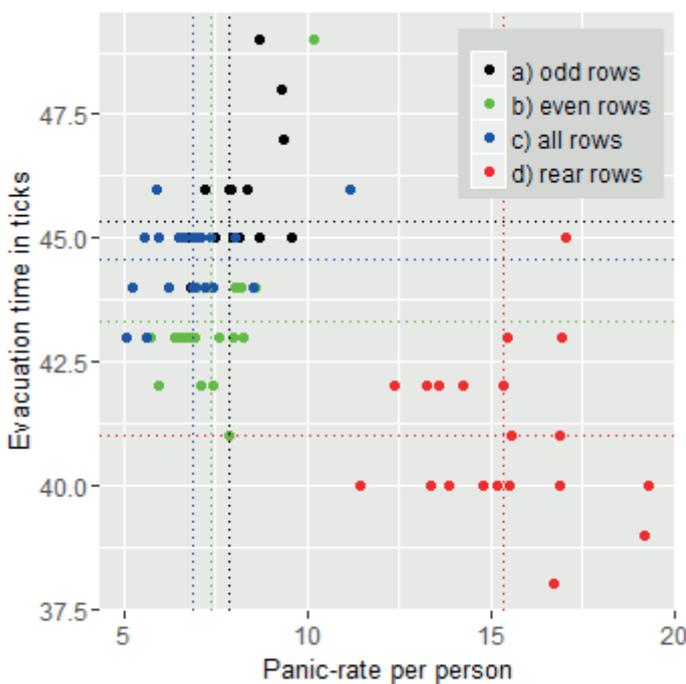
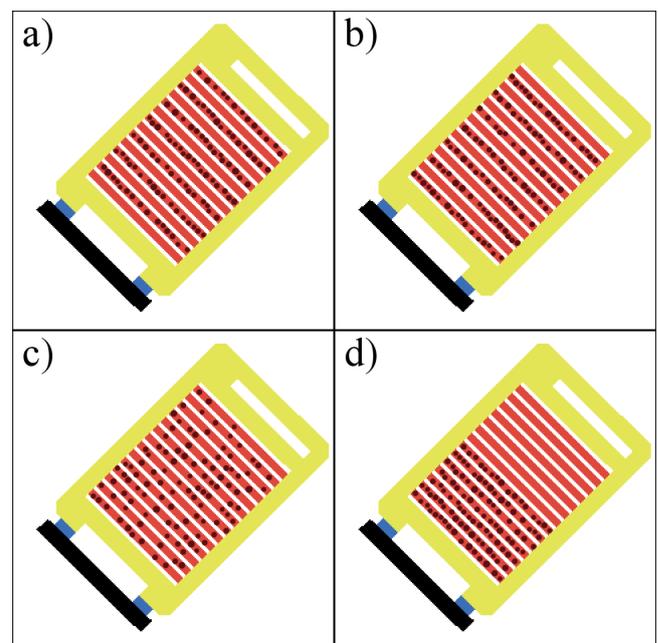


Fig. 14 The scatter plot of simulations according to seating scenarios.



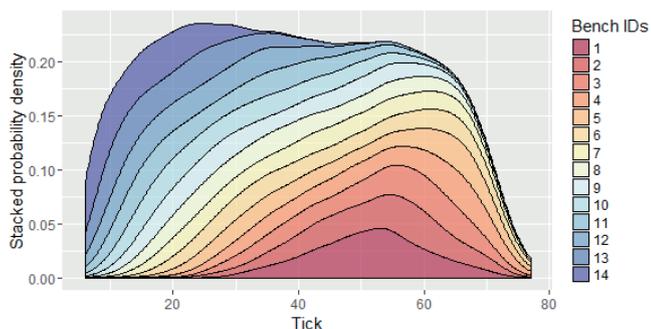


Fig. 15 The stacked probabilities of escaping during the simulation times. Plot created from 40 realizations.

In Fig. 15 it can be observed that the emptying started last time in the 1st row (See IDs in Fig. 4), close to tick 30. The first outgoing persons come from the rear benches (14-10). The first emptying row is the 14th, then comes the 13th and 12th, but this emptying trend seems to stop. It is interesting, that the peak evacuation moment of the 1st row foregoes some other rows (2nd, 3rd, ...6th), which are closer to the exits. Possibly this is due to that the front rows fill the aisles faster.

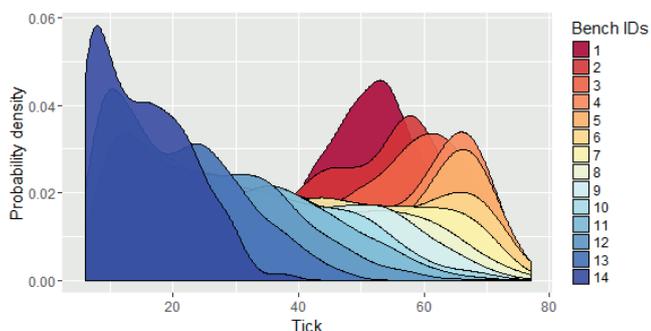


Fig. 16 The density plot of emptying benches.

Based on Fig. 16, the last evacuating persons come from the middle rows (5,6,7 and 8). We can observe that the high peaks of the middle evacuation times refers to the front rows, therefore appears a relevant mixture in the crowd.

Acknowledgement

The open-source model and the necessary files for the introduced example is shared on the following GitHub page:

<https://github.com/ewirth/evacuation>

References

- [1] de Smith, M. J., Goodchild, M. F., Longley, P. A. “*Geospatial Analysis*”. Fifth Edition, The Winchester Press, Winchester, UK. 2015. <http://www.spatialanalysisonline.com/extract.pdf>
- [2] Wilensky, U., Stroup, W. HubNet Guide. Center for Connected Learning and Computer-Based Modeling, Northwestern University. Evanston, IL. <http://ccl.northwestern.edu/netlogo/hubnet.html>.
- [3] Wilensky, U. (1998). NetLogo Flocking model. Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL. <http://ccl.northwestern.edu/netlogo/models/Flocking>.
- [4] Izquierdo, J., Montalvo, I., Pérez, R., Fuentetaja, V. S. “Forecasting pedestrian evacuation times by using swarm intelligence”. *Physica A: Statistical Mechanics and its Applications*, 388(1), pp. 1213–1220. 2009. <https://doi.org/10.1016/j.physa.2008.12.008>

- [5] Helbing, D., Farkas, I., Vicsek, T., “Simulating dynamical features of escape panic”. *Nature*, 407(6803), pp. 487–490. 2000. <https://doi.org/10.1038/35035023>
- [6] Gershenfeld, N. “*The Nature of Mathematical Modeling*”. Cambridge University Press, 2011.
- [7] Crooks, A., Croitoru, A., Lu, X., Wise, S., Irvine, J. M., Stefanidis, A. “Walk This Way: Improving Pedestrian Agent-Based Models through Scene Activity Analysis”. *ISPRS International Journal of Geo-Information*, 4(3), pp. 1627–1656. 2015. <https://doi.org/10.3390/ijgi4031627>
- [8] Almeida, J. E., Kokkinogenis, Z., Rossetti, R. J. F. “NetLogo Implementation of an Evacuation Scenario”. WISA’2012 In: Fourth Workshop on Intelligent Systems and Applications. Madrid, Spain. 2012.
- [9] Franceschetti, S., Sorrentino, D., Mussi, F., Pasolli, M. “GRASS GIS 7.2.svn Reference Manual”. <https://grass.osgeo.org/grass72/manuals/r.walk.html>
- [10] The R Project for Statistical Computing. <https://www.r-project.org/>
- [11] QGIS Development Team, 2016. QGIS Geographic Information System. Open Source Geospatial Foundation Project. <http://www.qgis.org/>
- [12] Stefan Ziegler, CadTools, 2012. <http://plugins.qgis.org/plugins/cadtools/>
- [13] Dr. Alan Chan, Anthropometry Online. <http://personal.cityu.edu.hk/~meachan/Online%20Anthropometry/Chapter2/Ch2-17.htm>
- [14] How to Determine Stride for a Pedometer by Height & Weight | Chron.com. <http://livehealthy.chron.com/determine-stride-pedometer-height-weight-4518.html>
- [15] Viswanathan, V., Lee, C. E., Lees, M. H., Cheong, S. A., Sloot, P. M. A. “Quantitative comparison between crowd models for evacuation planning and evaluation”. *The European Physical Journal B*, 87(2), 2014. <https://doi.org/doi:10.1140/epjb/e2014-40699-x>