SafePath

An Agent-Based Framework to Simulate Crowd Behaviors

António Leitão[1], Sofia Sousa[2], Francisco Loio[3]
[1,2,3]INESC-ID/Instituto Superior Tecnico, University of Lisbon
[1,2,3]{antonio.menezes.leitao|sofia.sousa|franciscoloio}@tecnico.ulisboa.pt

Nowadays, many buildings need to accommodate large numbers and/or large concentrations of people. Despite the efforts to produce building designs that can safely evacuate occupants, accidents continue to happen with dramatic consequences. This happens, in part, because of the difficulty in anticipating the consequences of design decisions regarding building's evacuation performance. In order to improve the situation, one needs to resort to evacuation simulation tools. These, however, have two problems: (1) they require analytic building models that are difficult to produce manually, and (2) they tend to focus on evacuations under non-emergency conditions, where panic phenomena is not present. In this paper, we propose a combination between algorithmic design and different evacuation simulators that allows for the quick simulation of many design variations.

Keywords: *Agent-based Modelling, Algorithmic Design, Evacuation Performance, Evacuation Simulation*

INTRODUCTION

The world population is now bigger than ever and is increasingly concentrated in cities. As a result, architects are facing the need to design spaces that can safely accommodate people in large numbers and/or large concentrations, e.g., stadiums, concert halls, hospitals, and shopping malls. In addition, the implementation of novel architectural concepts also pose the question of how safe these concepts are to the occupants in the event of an emergency.

Recent examples of the dramatic consequences of emergency evacuations include the more than 1500 injured while watching a football game in Italy in 2017, and the more than 2200 deaths in the Hajj in Saudi Arabia in 2015. Mass events are a reality of our time and stampedes occur even without any physical trigger. In these situations, safety measures are determinant for the success of the event's outcome. Now, more than ever, studying crowd behavior in case of an emergency evacuation is becoming a significant part of performance-based design (Kuligowski et al. 2005).

Studying crowd behavior is not a simple task. People's reactions can be unpredictable and, thus, their simulation involves a large amount of complexity that traditional methods have difficulties to deal with. On the other hand, full-scale evacuation simulations are quite limited: (1) exposing real people to danger is not ethical and the absence of panic, which is characteristic of a real emergency scenario, makes people not to take the simulation seriously, providing little useful information to the analysis; (2) determining the evacuation time based in just one experiment is highly unreliable so, in order to generate valid data, it is necessary to perform repeated experiments, preferably with different people to avoid memory effects; (3) evacuations drills are usually performed after the construction is completed, thus any necessary modification to the design might delay the project and increase its cost.

To overcome these issues, a good alternative is a computational model that can reliably simulate crowd behaviors in an evacuation scenario of the intended building. This model could be used at any stage of the design process, thus informing the architect about the building's performance, including in earlier design stages, when design changes are easier to accommodate.

In the last years, research in this area proposed different models and techniques that led to the development of several tools such as EGRESS, EXODOUS, PATHFINDER, and SIMULEX (Gwynne et al. 1999). Some of these tools are based on Agent-Based Modeling (ABM), an approach used for simulating human behaviors in different scenarios, making it possible to model individual's characteristics and interactions. However, despite using ABM to simulate people movements in an evacuation scenario, some of these tools, e.g., PATHFINDER [1], lack the emergency factor, making them inappropriate for simulating panic situations, where phenomena such as herding and clogging emerges (Pan et al. 2007).

The goal of this paper is to present a framework, currently under development, for combining Algorithmic Design (AD) with evacuation simulation, handling both normal evacuations as well as evacuations under the emergency factor. The framework is intended for the analysis and optimization of a design in order to provide better performance in evacuation scenarios, while taking into consideration other factors such as construction cost and space constraints.

In this paper, we discuss crowd behaviors and the differences between normal and emergency evacuations, we explain how to formalize the individual's behaviors using ABM, and, finally, we present an overview of the integration between ABM and AD.

CROWD BEHAVIORS

The study of crowd behaviors has been evolving during the last decades, focusing primarily on the dynamics of crowds under normal situations where evacuations are smooth and orderly. Lately, with the increasing number of crowd disasters, research regarding the analysis of crowd behaviors in panic situations has been receiving a lot of attention (Helbing and Johansson 2009).

Normal Evacuations

The first work that was developed concerning crowd movements was based on non-emergency scenarios and, to address it, several models were proposed. Tools such as PEDROUTE or PATHFINDER were developed and have been applied in different areas, namely urban design, traffic management, or planning guidelines.

These tools only consider normal situations, where people tend to manifest some common attributes, including (1) searching for the most convenient way to an exit, i.e., the shortest and fastest path, (2) avoiding detours even when one exit is crowded, e.g., people tend to wait instead of searching for an alternative, and (3) self-organization.

Emergency Evacuations

In case of an emergency, most of the behaviors observed in a normal situation are replaced by others. (Almeida et al. 2011). The presence of panic is commonly motivated by the survival instinct, which is awakened in life-threatening situations.

However, behaviors similar to panic are also observed in crowds that are looking for something highly desired, e.g., running for discounts in "Black Friday" or looking for the best seats in a concert. In these situations, people tend to run as fast as possible without concern to the most convenient path. Moreover, when people are unfamiliar with the space layout, there is a tendency to run for the same exit where they entered even though that may not be the shortest or safest path. Also, the nervousness increases, which leads to the lack of orientation and to the emergence of physical forces (e.g., pushing) which are responsible for the most common cause of injuries and deaths in disasters involving crowd evacuations. Finally, phenomena like herding and clogging are extremely common in emergency scenarios as result of the loss of independency in panic situations: people tend to transfer control of their actions to others, creating a social contagion (Helbing and Johansson 2009), which explains why some exits are overcrowded while others are empty.

The resulting forces generated by physical interactions in panicking crowds can reach pressures up to 4450N/m, sufficient to bend steel barriers or take down brick walls (Helbing et al, 2000). As a result, people start to fall and acting as obstacles, blocking paths and exists, resulting in a further slower evacuation (Keating, 1982).To demonstrate the effects of this pressures, Helbing, Farkas and Vicsek, (2001) developed a pedestrian evacuation model which proved that a column right in front of an exit can, counterintuitively, increase the evacuation outflow in 50% by taking up the pressure from behind and thus reducing the number of injured people blocking the exits.

AGENT-BASED MODELING

Research and development on pedestrian dynamics has seen a rapid growth in recent years. Nowadays, there are several different approaches to model crowd behavior which differ in numerous characteristics, either in modeling the pedestrians as well as geometry. The fundamental variation is the scale at which the crowd is modeled. In macroscopic models, the crowd is described as a whole while, in microscopic models, every pedestrian is considered as an individual and the global behavior of the crowd emerges from all individuals' behaviors and interactions. For this last case, Agent-based modeling (ABM) is a powerful paradigm that has been actively used in several areas (Macal and North 2005). ABM is defined as a collection of autonomous agents acting as decision-makers, that can range from purely reactive to more complex deliberative agents (Bonabeau 2002).

In this paper, we focus on modeling human systems using ABM. With this paradigm, it is possible to model individual characteristics of humans, such as age, gender, and experience, influencing the interactions with the surroundings and other agents. To this end, we will use the PATHFINDER tool, an agent-based simulation tool.

The ability to model crowd motion from individual behaviors and interactions, is what makes ABM such a valuable tool for simulating human systems (Bonabeau 2002). However, the modeling of the agents representing human beings is still a challenging task. The Belief-Desire-Intention (BDI) is a well-known architecture, proposed by Michael Bratman in 1987, that allows to model such complex agents, being the most studied and successful model to represent reasoning agents (Georgeff et al. 1998). In this paradigm, the decision making process of the agent in an emergency scenario is a deliberative process based on (1) human desires, e.g., exit the building alive, (2) beliefs that express the knowledge of the world, e.g., where the nearest door is, and (3) resulting intentions that are structured into plans to accomplish the desires, e.g., the set of actions that define the agent's path to the exit door.

EMERGENCY EVACUATION

None of the current simulation tools can fully address all human and social behaviors present in panic situations. However, simulation models that are based on realistic assumptions regarding human behaviors in emergency scenarios can provide a great contribution to engineering and public safety. To successfully simulate an emergency scenario, several social aspects must be modelled, such as the presence of leaders, the experience and knowledge of the occupants, the nervousness, the persistence, and the

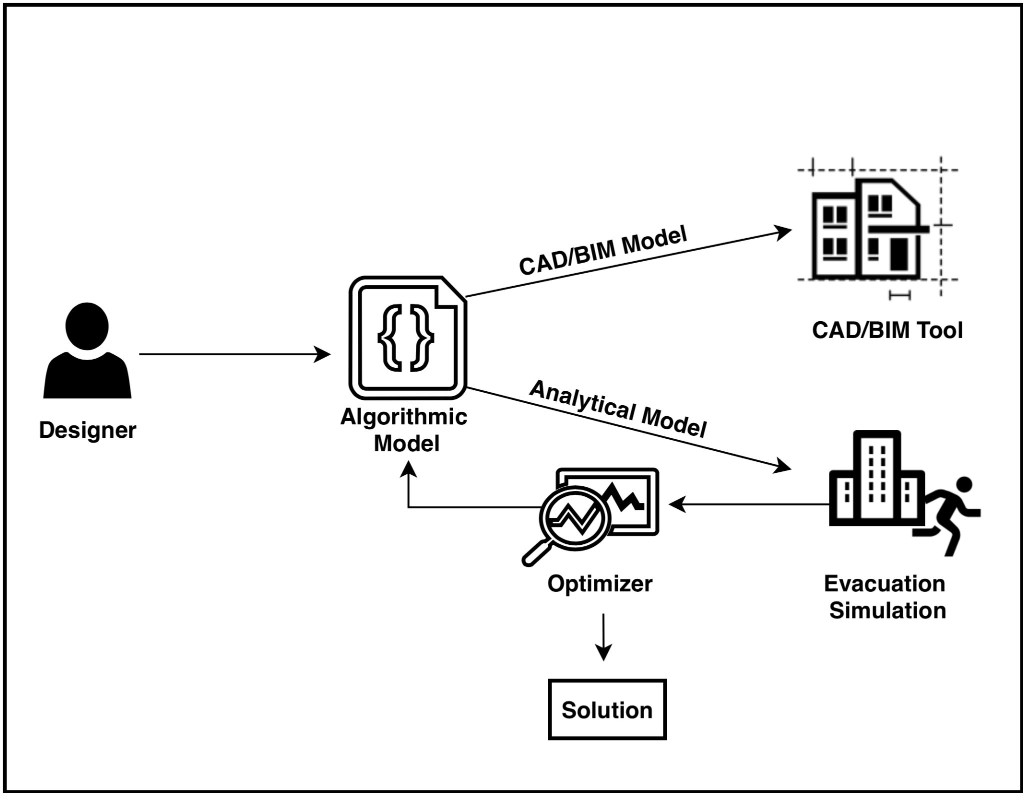

Figure 1
System architecture: the user creates an algorithmic description of a design, which is then used to generate regular 3D models for visualization, as well as specialized analytical models for different analysis tools, particularly, for evacuation simulation. When combined with an optimizer, the framework can automatically discover the design variation that has the best performance in what regards evacuation.

competitive/collaborative behaviors.

We are currently working on a new simulation framework to extend a previous one (Sousa et al. 2017) with a new ABM implementation that takes into account panic behaviors. The main objective of this framework is to use ABM coupled with AD, not only for analysis purposes, but also to optimize designs regarding their evacuation performance. To this end, the ABM implementation is treated as a fitness function and is used for the optimization of the parametric design generated from the AD framework. Figure 1 describes the integration of the evacuation simulator in the AD process.

The proposed framework depends on the use of AD. Initially, the user creates an algorithmic description of a design which, when executed, generates a 3D model of the design on selected Computer-Aided Design (CAD) or Building Information Modelling (BIM) tools. However, the framework also supports backends dedicated for simulation. In theses cases, the same algorithmic description of the design is used to generate specialized analytical models for different analysis tools, particularly, for evacuation simulation. We plan to include, in the framework, an optimizer that can automatically discover the design variation that has the best performance in what regards evacuation.

In order to clarify the results produced by the optimization, the framework also presents the designer a set of graphical explanations, namely, the effect in the evacuation times of the different design choices.

Due to the ethical difficulties that lie with validating panic situations in real life, we plan to validate our simulator by comparing it with others, e.g., PATHFINDER, for normal evacuations, or SIMULEX for emergency evacuations.

EVALUATION

In order to evaluate our proposal, we adapted Khepri, an algorithmic design tool, to work with an evacuation simulator. Khepri is a descendant of Rosetta (Lopes and Leitão 2011), and is currently being developed to become its replacement. Khepri shares with Rosetta the ability to have multiple backends for different purposes. This means that, from a single algorithmic description of a building, Khepri can generate different models, e.g., a 3D model for visualization, or different analytical models for different types of analysis. In the case of evacuation analysis, we have two possible backends: one, that is still a work-in-progress, is dedicated for simulation of evacuations under panic conditions, and the other, for non-panic evacuations, is capable of generating analytical models for PATHFINDER, a well-established and validated simulator. Given that the simulator for evacuation under panic conditions is not yet validated, in this paper we will focus on the second backend and we will explain the connection between the algorithmic design tool and the PATHFINDER simulator.

To use a realistic case study, we decided to evaluate our proposal on an emblematic building: the Bauhaus, one of Europe's most influential and revolutionary schools of design. It was founded in 1919, by Walter Gropius, a German architect who intended to unite the instruction of the fine arts with technology. Its Dessau building, designed by Gropius himself, is an embodiment of the principles of the school. Its innovative use of materials, and its simple and straightforward design contributed to the development of what is known as the modernism style. Nowadays, the Bauhaus is considered one of the greatest influences on modern architecture.

In order to test the evacuation performance of the Bauhaus building, as well as possible improvements to that performance, we created an algorithmic version of the building. Obviously, the parameters of the algorithm can be instantiated with values that allow the original building to be exactly reproduced, as is possible to see in Figure 2. However, it is possible to change these parameters so that different versions of the building can be produced. Given that we did not want to fundamentally change the building, we considered an hypothetical situation where the building would be subjected to a remodeling effort in order to improve its safety. To that end, many different things can be changed but, for evaluation purposes, we decided to focus on just one change that can trivially be implemented in the algorithmic model and that allows us to easily visualize its impact: changing the width of all doors in the build-

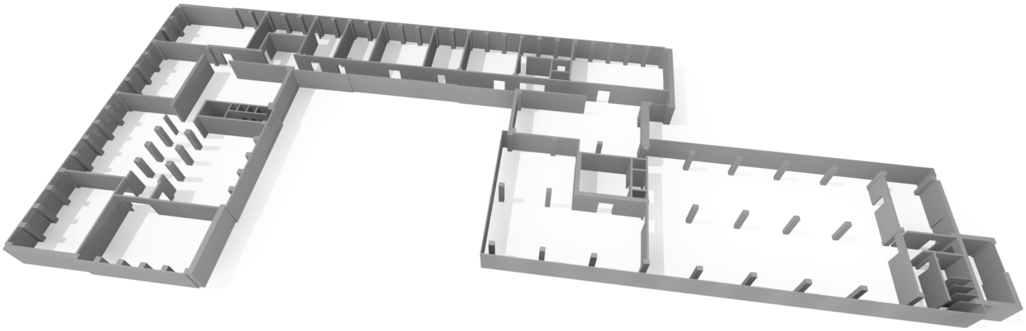

Figure 2
The algorithmically generated model of the first floor of the Bauhaus building.

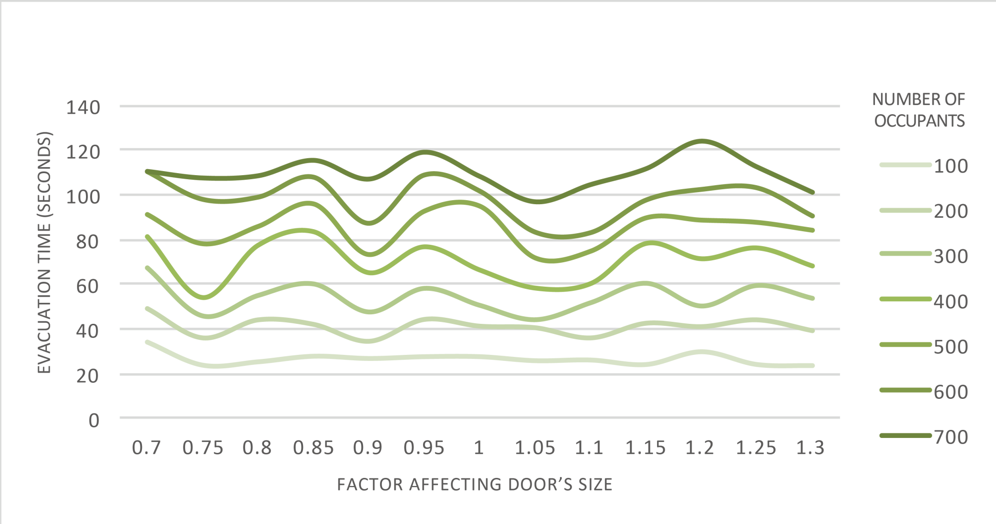

Figure 3
A graphic with the evacuation time for different doors' width and different concentration of people.

ing. It is known that this is a dimension that can have dramatic effects on the outcomes of an evacuation (Sousa et al. 2017) and, as such, it becomes a relevant use case for our proposal.

In order to measure the effects of the doors' width, we changed just one line in the algorithmic description of the Bauhaus building so that each door would have its width enlarged (or reduced) by a given fraction of the original design. The idea was to test the evacuation characteristics of the building as if, during its remodeling, the architect decided to make the exits, for example, 10% larger than they were in the original project. In fact, we tested doors' size that were between 70% and 130% of their original sizes. For each given factor, the algorithm version of the building was used to generated a corresponding analytical model, which was then given to PATHFINDER and analyzed for different numbers of occupants. The graphic in Figure 3 shows the evacuation time for the different doors'size and for different numbers of occupants. Figure 4 illustrates a density map produced by PATHFINDER during the simulation, showing, with different colors, the number of people present at any given place.

There are a few important conclusions that one might extract from this study.

The first one is that by including in the algorithmic design tool a dedicated backend for evacuation simulation, it becomes almost trivial to evaluate the evacuation performance of different versions of a building design. In fact, one simply needs to change the values of the design parameters and regenerate the corresponding analytical models. This is in stark contrast with the traditional simulation process, where the architect needs to manually adapt or create an analytic building model so that it can be used by the simulation tool. For each change, additional manual labor needs to be done in order to adapt the analytical model. Given all these manual efforts, it is not surprising to see that these simulations tend to be done only in later stages of the design process, when changes are no longer expected. Unfortunately, that is also the stage where the results of the simulation have limited effect on the design.

A second important conclusion is that it becomes trivial to get additional insights regarding the

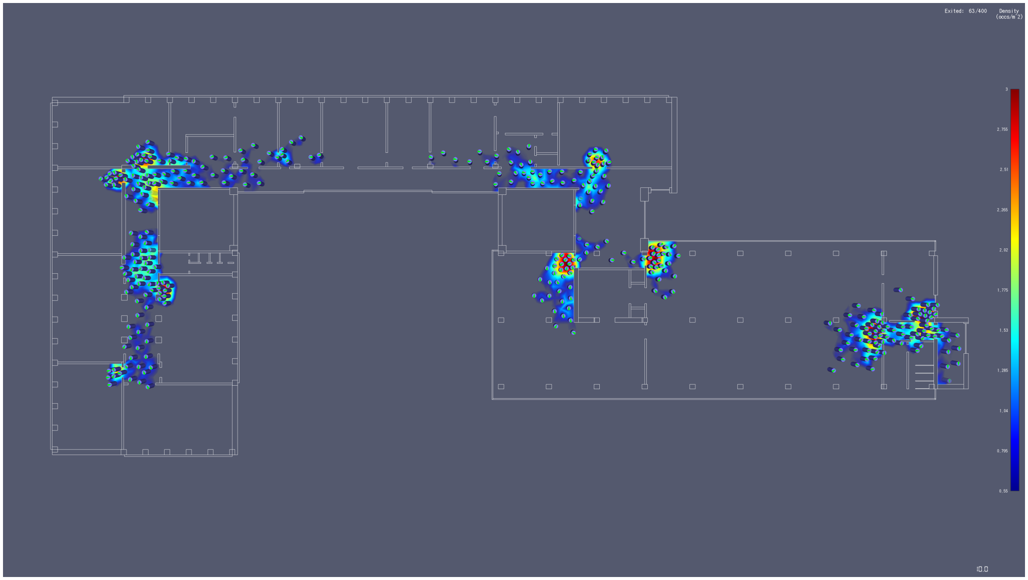

Figure 4
A snapshot taken after 10 seconds of the evacuation simulation of 400 people from the Bauhaus building, in which each door's width has 75% of its original size.

simulation. As an example, during the evaluation of our case study, we started by measuring evacuation times for door's sizes increasing and decreasing in multiples of 10%, and we then became surprised not only with the non-monotonicity of the evacuation times, but also with the lack of significant improvements. According to PATHFINDER's results, it looked like the original design was the best possible, as evacuation times would tend to go up both when we made doors larger and well as when we made them smaller. In order to get a clearer picture, we decided to test again, but this time using increments and decrements that were multiples of 5%. Note that this was a trivial change that could be evaluated in a matter of minutes. The results, visible in Figure 3, show that, indeed, the original design was very good, but they also show that evacuation times can be improved if we enlarge all doors by just 5%. This improvement can be dramatic when the building contains large numbers of occupants.

A third conclusion is that it might be important to also test some non-parametric features. For example, we discovered that, in this case study, the presence or absence of an additional door could have a huge impact on the evacuation performance. This is a binary feature that is trivial to implement but not trivial at all to anticipate. This means that, despite all the automation provided by the combination between algorithmic design and evacuation simulation, it is still important to have the architect in full control of the process, so that, as he gets more and more insight regarding the evacuation, he starts experimenting with less parametric design features. This is particularly important when the framework is being used for automated optimization as, in this case, we might miss some design changes that would have a considerable impact on the improvement of the evacuation times.

CONCLUSIONS

Due to the development of buildings capable of accommodating large numbers and/or large concentrations of people, and to the increasing number of crowd disasters that have been happening, the ability to deal with evacuations is becoming critical. The difficulties in evaluating these evacuations with full-scale drills and the associated ethical problems pose the need to perform computational simulations. However, these simulations present two problems: (1) they require analytic building models that are difficult do produce manually, and (2) they tend to focus on evacuations under non-emergency conditions.

In this paper we proposed a framework based on the combination between algorithmic design and different evacuation simulators that allows for the quick simulation of many design variations. We evaluated our framework with PATHFINDER, a well-known validated evacuation simulator. However, despite its usefulness for simulating normal evacuations, PATHFINDER does not correctly handle emergency evacuations.

To overcome this problem, we are currently developing a new evacuation simulator based on an ABM approach that also handles emergency situations, considering the several human and social behaviors that emerge in these events.

ACKNOWLEDGMENT

This work was supported by national funds through *Fundação para a Ciência e a Tecnologia* (FCT) with reference UID/CEC/50021/2013.

REFERENCES

Almeida, JE, Rosseti, R and Coelho, AL 2011 'Crowd Simulation Modeling Applied to Emergency and Evacuation Simulations using Multi-Agent Systems', *DSIE'11 - 6th Doctoral Symposium on Informatics Engineering*, Engineering Faculty of Porto University, Porto, pp. 93-104

Bonabeau, E 2002 'Agent-based modeling: Methods and techniques for simulating human systems', *Proceedings of the National Academy of Sciences, 99*, pp. 280-7287

Georgeff, M, Pell, B, Pollack, M, Tambe, M and Wooldridge, M 1998, 'The belief-desire-intention model of agency', in Müller, JP, Rao, AS and Singh, MP (eds) 1998, *International Workshop on Agent Theories, Architectures, and Languages*, Springer-Verlag Berlin Heidelberg, pp. 1-10

Gwynne, S, Galea, ER, Owen, M, Lawrence, PJ and Filippidis, L 1999, 'review of the methodologies used in the computer simulation of evacuation from the built environment', *Building and environment*, 34(6), pp. 741-749

Helbing, D, Farkas, IJ and Vicsek, T 2000, 'Simulating dynamical features of escape panic', *Nature*, 407, p. 487–490

Helbing, D, Farkas, IJ and Vicsek, T 2001, 'Crowd disasters and simulation of panic situations', in Schellnhuber, HJ, Bunde, A and Kropp, J (eds) 2001, *Science of Disaster: Climate Disruptions, Heart Attacks and Market Crashes*, Springer

Helbing, D and Johansson, A 2009, 'Pedestrian, crowd and evacuation dynamics', in Meyers, AR (eds) 2009, *Encyclopedia of Complexity and Systems Science*, Springer, Heidelberg, pp. 6476- 6495

Keating, JP 1982, 'The myth of panic.', *Fire Journal*, 147, pp. 56-61

Kuligowski, ED, Peacock, RD and Hoskins, BL 2005, *A Review of Building Evacuation Models*, Gaithersburg, MD: US Department of Commerce, National Institute of Standards and Technology

Lopes, J and Leitão, A 2011 'Portable Generative Design for CAD Applications', *ACADIA 11: Integration through Computation [Proceedings of the 31st Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)]*, Banff, pp. 196-203

Macal, CM and North, MJ 2005 'Tutorial on agent-based modeling and simulation', *Simulation conference, 2005 proceedings of the winter IEEE*, p. 14

Pan, X, Han, CS, Dauber, K and Law, KH 2007, 'A multi-agent based framework for the simulation of human and social behaviors during emergency evacuations.', *Ai & Society*, 22(2), pp. 113-132

Sousa, S, Caetano, I and Leitão, A 2017 'Saving Lives with Generative Design and Agent-based Modeling', *ShoCK! - Sharing Computational Knowledge! - Proceedings of the 35th eCAADe Conference*, Rome, Italy, pp. 93-102

[1] https://www.thunderheadeng.com/