MEng Project Final Report

Computer modelling of panic evacuations

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6th April 2017

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A thesis submitted to the School of Engineering for the degree of
MEng Mechanical Engineering

Abstract

The pedestrian dynamics models developed over last 50 years proved useful in understanding the human behaviour during panic evacuations. Simulations became an important tool allowing for better design of infrastructure, and predicting and mitigating dangerous crowd situations. The main objectives of the project were to understand and implement an appropriate agent-based model, test its predictive capabilities, investigate a panic evacuation scenario, and propose ideas for preventing fatalities and injuries.

The Helbing social force model was implemented in the OpenFOAM framework. It uses a microscopic approach where every pedestrian can be tracked and simulated as a distinct entity. Motion of agents is described as if they would be subject to "social forces" representing their motivations to perform movement. Predictive capabilities of the model were tested against empirically observed crowd phenomena (like lane formation or arching) and published data from a movie theatre experiment and a real earthquake evacuation. Finally, the fully calibrated model was used to investigate the evacuation of The Station nightclub where panic tragedy occurred in 2003. Simulations were run to identify the main bottlenecks and analyse the effect of geometry modifications on the outflow of people.

The validation procedure suggested that the model was capable of correctly representing the behaviour of high-density crowds escaping through narrow passages. The position of the main bottleneck identified in the nightclub simulations agreed with the information provided in the official accident report. It was also found that a removal of the vestibule walls in the main exit area would have resulted in a 31.2% decrease of the total evacuation time and most likely prevented many injuries and fatalities. Lack of common standard procedures of calibration was considered the main limitation in the project. However, the agentFOAM code managed to demonstrate the usefulness of panic evacuation models in studying crowd behaviours and mitigating potentially dangerous situations.

Personal Statement

The project concerning pedestrian dynamics evolved from the Micro & Nano Flows research group whose already existing frameworks, computational methodology and strategy available could be applied to model agent-based systems. A similar topic was studied by a BEng student last year who managed to create a MATLAB code to study crowd evacuations. In my project, the social force model was implemented with C++ scripting in the OpenFOAM software.

The initial steps involved researching various social force models, their implementation and rigorous testing, before proceeding with the validation cases and investigation of The Station nightclub evacuation. The agentFOAM module of OpenFOAM was written and provided by my supervisor Matthew Borg, who developed the advanced parts of the code. He also provided me with support in tackling the programming issues I encountered. Most of my work was concerned with the highest level of the code where I defined agents' properties, geometry of the environment, and other parameters necessary to set up simulations. However, over a few months I managed to learn enough of the C++ syntax and the OpenFOAM structure to implement and modify the solver algorithms. Those included the agent-walls detection and repulsion, or the visibility graph path finding.

A lot of effort was also put into understanding in detail how different agent-based models work. Similarly, I ensured that the highest quality verification, validation and calibration procedures are conducted, as they were key to producing a reliable model. This part of the project turned out to be the most time-consuming as it involved setting up multiple cases and testing various models and parameters. Defining agent positions, their paths or borders was a precise and tedious job due to the nature of the code which allowed for a lot of flexibility at the cost of ease of use. The more models and features were implemented in agentFOAM, the more difficult it became to navigate.

I believe that, during the project, I gained important software skills (Linux, C++) and managed to learn about the complexity of numerical methods used in studying panic evacuations. No additional workshop time, materials, laboratory space or other services were requested for this project.

I declare that this thesis is my original work except where stated.

Signature	06.04.2017 Date

Acknowledgements

I am very grateful to my thesis supervisor, Matthew Borg, for his guidance and invaluable help with any software and engineering related issues I encountered in the course of work. His passion for the subject and enthusiasm kept me motivated during the whole project, and his coding skills were indispensable when implementing the agentFOAM model.

I would also like to thank Efe Madranefe and Guillermo Fernandez Bautista, who also worked on pedestrian dynamics projects, for many productive and fun discussions.

Contents

List of Symbols

Δt	Value of one time step
η	Fluctuation force strength parameter
κ	Tangential physical force parameter
$\mathbf{a}_i$	Acceleration of agent i
$\mathbf{e}_i^0$	Agent's desired direction of motion
$\mathbf{f}_{ij}$	Agent-agent social force
$\mathbf{f}_{iW}$	Agent-walls social force
$\mathbf{r}_i$	Position of agent i
$\mathbf{v}_i$	Velocity of agent i
$\boldsymbol{\xi}$	Fluctuation force
σ	Standard deviation of a normal distribution
τ_i	Relaxation time of agent i
A_i	Social force maximum strength parameter
B_i	Social force interaction range parameter
k	Normal physical force parameter
m_i	Mass of agent i
r_{cut}	The cutoff distance for the agent-wall interaction force
r_{offset}	The offset distance of borders vertices in the visibility graph algorithm
v_i^0	Agent's desired speed
$v_{\max}$	Agent's maximum allowable speed

Glossary

ABM Agent-based modelling. Microscopic computational method modelling pedestrians as distinct independent entities.

Agent scheduling Definition of a series of tasks to be completed by an agent. In the context of this report, it includes specifying the routes to be followed by an agent.

agentFOAM A framework for solving agent-based simulations within OpenFOAM.

BC Boundary condition.

CA Cellular automata. A discrete model based on a regular grid of cells.

CFD Computational Fluid Dynamics.

ERD Euclidian Relative Difference.

NIST National Institute of Standards and Technology. A measurements standards laboratory of the United States Department of Commerce.

OpenFOAM A free, open-source CFD software with C++ libraries allowing for the development of customised numerical solvers.

Open-source software Software whose source code is available for modification or enhancement by anyone.

V&V Verification and validation.

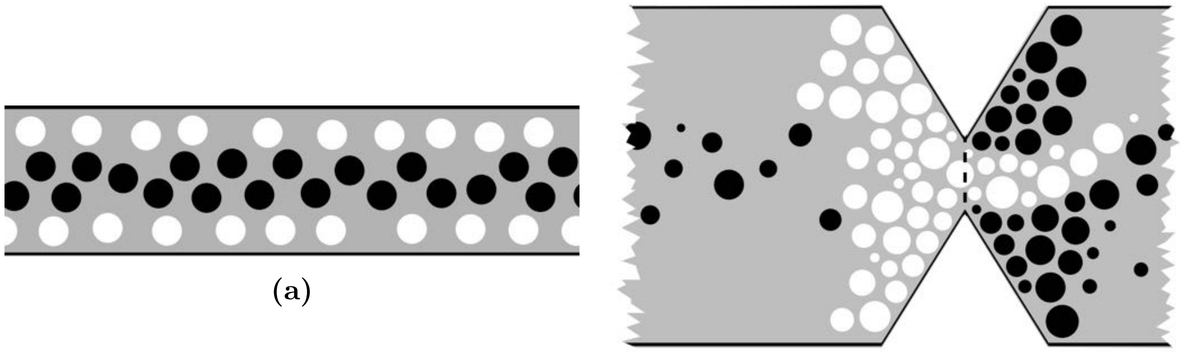
1 Introduction

One of the most disastrous forms of collective human behaviour is the kind of crowd stampede induced by panics, often leading to fatalities as people are crushed or trampled. Aeroplanes, cruise ships, airports, nightclubs, concerts and street gatherings have all experienced such emergency evacuations in the past. For example, The Station nightclub fire in Rhode Island in 2003 triggered a mass evacuation of revellers, resulting in 100 fatalities and injuring more than 200 [1]. Moreover, the frequency of such disasters is expected to be increasing with the number and size of mass events and the global population growth.

The motivation of the project is to understand and accurately model the human behaviour during panic evacuations. Such a model is important in studying the dynamics of human crowds and can be used to prevent disasters from happening in the future. It can serve as a tool allowing for designing the infrastructure more carefully and better planning of forthcoming mass events to avoid any injuries or fatalities to humans.

Modelling crowd motion accurately is a challenging task and agent-based modelling (ABM) will be used throughout the project as it is capable of capturing the complexity of human behaviour on an individual level. This computational method enables modelling of people as discrete entities with specific goals and sets of well-defined mathematical and physical rules describing their interactions with other agents and the environment. It can, therefore, be used to predict and mitigate potentially dangerous crowd situations like pressure build-ups and clogging.

The main objective of the project is to understand and implement an appropriate agent-based model for the motion of highly-stressed humans during evacuations. The next goal involves verifying and testing the model against empirically observed crowd phenomena like lane formation or oscillations at bottlenecks illustrated in Figure 1. This



(a)

(b)

Figure 1: Two empirically observed pedestrian dynamics phenomena which can be reproduced using simulations: (a) lane formation, (b) oscillations at bottlenecks [2].

is followed by a calibration procedure and validation of the predictive capabilities of the model against data from published examples like the classroom evacuation during an earthquake [3] or the theatre evacuation exercise [4]. The final aim is to use a fully calibrated and validated model to investigate the evacuation procedure during The Station nightclub fire in Rhode Island. Supported by the simulations, scientific ideas for preventing fatalities and injuries are proposed.

2 Literature Review

The following section aims to provide an overview of the most significant research carried out in the field of panic evacuation modelling. Behavioural rules, self-organisation phenomena and their importance in pedestrian dynamics are discussed first. Different ways of modelling human crowds are then presented and evaluated. Finally, Helbing's social force model is described in detail as it serves as a starting point for implementing a realistic agent-based model in this project.

2.1 Introduction to crowd dynamics modelling

As pedestrians are complex living beings, their detailed individual behaviour is highly unpredictable and difficult to model. However, it is possible to simulate the dynamics of crowds by identifying the most important behavioural rules governing the collective pedestrian motion [5].

- Target - in most cases, people move in a bounded space defined by available walkways and roads as well as obstacles. They also have a desired destination to be reached and speed at which they want to travel. Those can vary depending on familiarity with the environment.

- Repulsion - people tend to avoid collisions with other pedestrians. This causes them to avoid crowded areas and stop when getting too close to others.

- Attraction - sometimes, the tendency of people to stay together becomes important. This, for example, applies to families or groups of friends.

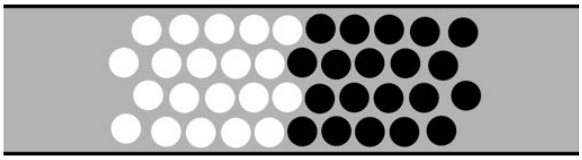
- Keeping direction - in addition to having a desired destination, people tend to avoid changing directions too often as it is tiresome and inefficient.

Such local behavioural rules affecting all pedestrians can often lead to self-organisation phenomena. It is observed that human crowds of sufficiently high density exhibit features of collective behaviour in which dynamics of one entity is affected by other entities [6]. In normal situations, the self-organisation phenomena includes effects like lane formation or oscillations at bottlenecks as shown in Figure 1.

It is also important for mathematical models to account for a transition from normal to panic conditions as some of the behavioural rules change or cease to apply in highly stressful situations. For example, the interactions become physical in nature, people tend to move faster and stop any kind of collaboration [5]. In addition to normal situation phenomena discussed in Section 1, new empirical effects like "freezing by heating" [7] or arch-like blocking of exits [2] are observed in panic conditions (see Figure 2).

2.2 Classification of models

Pedestrian dynamics has been studied for a little over fifty years now [8, 9, 10]. A number of different simulation models have been proposed over time and most of them can be divided into two types: macro and microscopic.



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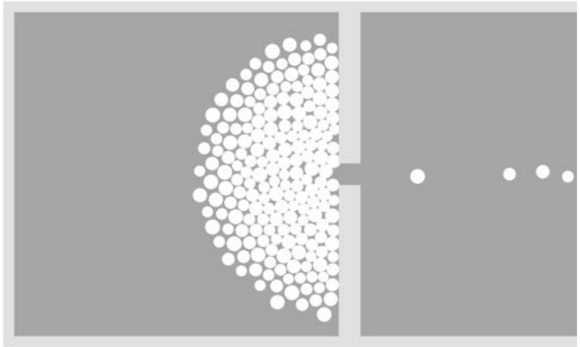


(b)

Figure 2: Collective phenomena in panic situations: (a) "freezing by heating" representing the effect of oppositely moving pedestrians getting nervous which leads to a blocked situation [7], (b) arch-like blocking of an exit observed when people rush to escape [2].

2.2.1 Macroscopic models

Macroscopic models base heavily on an assumption that a crowd being modelled is concentrated enough to be treated as a continuum, where conservation laws apply. It can then be described by locally averaged quantities like density or velocity which depend on both time and position [5]. The models are, therefore, based on Navier-Stokes equations and are sometimes referred to as fluid dynamics models [6]. Such macroscopic models are often in a form of partial differential equations and apply conservation laws to describe relationships between speeds and densities [11]. Henderson [12] was the first to observe that human crowds can behave similar to gases or fluids and proposed a model which managed to reproduce the time and space dependent patterns of motion.

There is, however, many shortcomings to the macroscopic models when it comes to panic evacuation modelling. First of all, real pedestrians do not obey energy and momentum conservation laws, which contradicts the model's main assumption. A realistic macroscopic model would need to account for local interactions and various manoeuvres like accelerating, stopping or sudden changes of direction [13]. Moreover, Navier-Stokes equations are nonlinear and coupled which makes them more difficult to solve [6]. Hence, most of the existing models for pedestrian flow are of microscopic nature [11].

2.2.2 Microscopic and agent-based models

In microscopic models, it is assumed that every pedestrian can be tracked and modelled as a distinct entity. The interactions between humans and obstacles are then simulated on an individual level. This results in an overall crowd behaviour. As mentioned in Section 1, agent-based models are also a type of microscopic model comprising of autonomous, interacting agents. According to Macal [14], agents are considered to have the following properties:

- Agents are autonomous, self-directed and can function independently within the domain.
- Agents are modular and self-contained. Each has their own characteristics, attributes or behaviours.

- Agents interact with other agents and rules are defined to describe those interactions. This can, for example, include collision detection, other agent recognition or communication.

Those properties make ABM a highly flexible method. The rules governing the agents can be easily controlled to decrease or increase the complexity of the model. Helbing [13] states that this makes ABM more favourable for studying pedestrian dynamics and panic evacuations than the macroscopic models. Over time, many microscopic ABM models have been proposed and the most important ones are discussed below.

Cellular automata Cellular automata (CA) is a rule-based method that does not rely on differential equations. A 2D domain for the simulation is first discretised into a mesh. Each cell of the created mesh can be occupied only by one agent and the motion calculations are always performed in parallel for all the agents present in the domain. The pedestrians are given a matrix of preference which describes their probabilities to move to one of the nine cells as shown in Figure 3. Each of them is allowed to move by a maximum distance of one cell only during one timestep [6]. Collisions are avoided by having the agent with highest probability move to the next cell when two of them are competing. If all nine cells are taken, an agent does not move. The advantages of this method are its easy to implement rules and a very good computational efficiency. However, the models that can be implemented are simple and only short-range (neighbour) interactions are considered in the calculations [5].

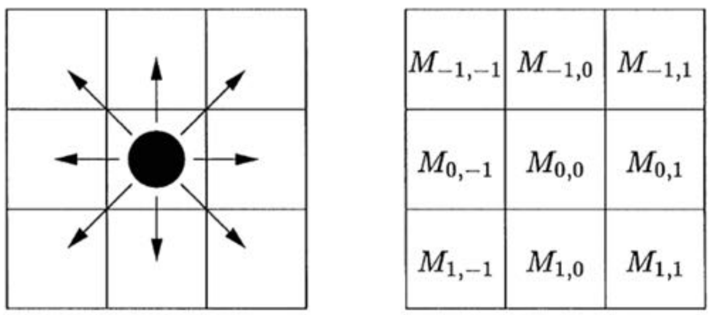


Figure 3: An agent, its possible movements and the associated matrix of preference [6].

Social force model The social force model was first introduced by Helbing in 1995 [15]. In comparison to CA, it is not based on a discretised grid but on a continuous 2D space. Helbing suggests that the motion of pedestrians can be described as if they would be subject to "social forces" representing their internal motivations to perform movement. The key components include terms describing acceleration towards the desired velocity of motion, keeping a certain distance from other pedestrians and obstacles, and attractive effects. Examples of simulations using the social force model were illustrated in Figure 1 and Figure 2. The model has been praised for being able to describe quite accurately some empirically observed phenomena. The realistic patterns emerge in the social force model simulations due to the nonlinear interactions between pedestrians [5].

Other models In the broad overview of the crowd motion simulation models performed by Duives [16], velocity-based models, hybrid models, behavioural models and network models are also mentioned as potentially viable methods among the continuum (macroscopic), social force model and cellular automata. Moreover, game theory models have also been suggested for modelling panic evacuations [17]. However, Duives states that cellular automata and the social force model are capable of reproducing the largest set of real crowd motion phenomena and are, therefore, more advantageous.

It was decided that the social force model (which can be classified as an agent-based model) will be investigated in this project. That method was chosen as it proves to accurately represent real crowd phenomena while being relatively straightforward to implement and modify as different force terms can be easily added or manipulated. Moreover, OpenFOAM software with its agentFOAM module will be used during the project and their framework is very suitable for implementation of the social force model. A detailed description of the method is presented in Section 2.4.

2.3 Path finding

After initialising agents in a panic evacuation model, the first step is to define their route choices. This can be done at a local or global level by defining agents' intermediate or final destinations respectively. Different algorithms can then be employed to calculate the preferred route [18]. Typically, it is the fastest or shortest route, but can also be an arbitrary user-defined rule. Most evacuation models generally assume that an agent "knows" from the beginning where their target(s) will be. Examples of the most common types of path-finding algorithms are shown in Figure 4. Various methods were explored in the project to find the optimum one. The best algorithm choice ultimately depended on the situation and environment being simulated.

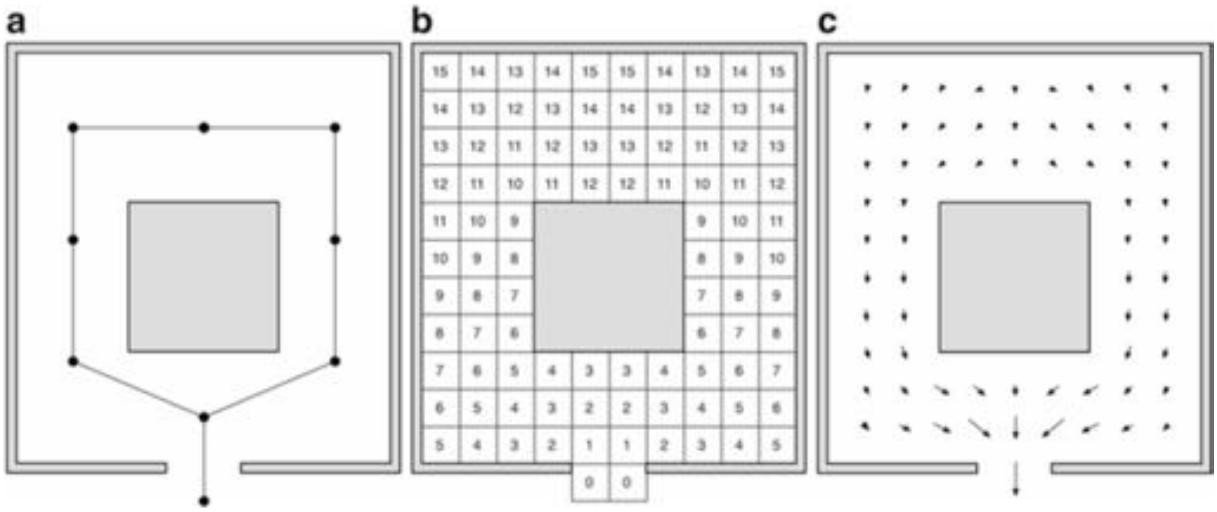


Figure 4: Examples of path-finding algorithms. (a) Graph-based solution. (b) Distance map solution. (c) Vector field solution. [18]

2.4 Helbing's social force model

2.4.1 Initial formulations for normal and panic situations

As mentioned in Section 2.2.2, the social force model was first presented by Helbing in 1995 [15]. It mainly discussed simulations of pedestrians in normal (non-panic) situations to show self-organisation and collective behaviour of crowds. The model succeeded at describing many phenomena realistically despite being relatively simple. In 2000, a paper about dynamical features of escape panic was published by Helbing [19]. The model presented in this paper will be used as a base for this project and is described below. Vectors are represented by symbols in bold.

The model uses Newton's second law to relate the acceleration of a given agent to the social forces acting on them. We first assume N pedestrians, each being assigned with mass m_i, certain desired speed v_i^0 and a desired direction of motion $\mathbf{e}_i^0$. As every agent has their desired speed at which they want to travel, they tend to correspondingly adapt their actual velocity $\mathbf{v}_i$ with a certain "relaxation time" τ_i. At the same time, the agent tries to keep a certain distance from other agents j, and walls W. This is modelled by interaction forces $\mathbf{f}_{ij}$ and $\mathbf{f}_{iW}$ respectively. The acceleration (change of velocity in time t) of an agent is then expressed by the following equation:

$$m_i \frac{d\mathbf{v}_i}{dt} = m_i \frac{v_i^0(t)\mathbf{e}_i^0(t) - \mathbf{v}_i(t)}{\tau_i} + \sum_{j(\neq i)} \mathbf{f}_{ij} + \sum_{W} \mathbf{f}_{iW}. \tag{1}$$

The first term on the right hand side of the equation is also known as the "will" force as it always pushes the agent in their desired direction. The change of position $\mathbf{r}_i(t)$ can be found from velocity $\mathbf{v}_i(t) = d\mathbf{r}_i/dt$. The agent-agent interaction force $\mathbf{f}_{ij}$ is then described by the equation

$$\mathbf{f}_{ij} = \Big(A_i \exp\big((r_{ij} - d_{ij})/B_i\big) = kg(r_{ij} - d_{ij})\Big)\mathbf{n}_{ij} + \kappa g(r_{ij} - d_{ij})\Delta v_{ij}^t \mathbf{t}_{ij}, \tag{2}$$

where $A_i \exp\big((r_{ij} - d_{ij})/B_i\big)\mathbf{n}_{ij}$ is the social repulsive component of the force representing the psychological tendency of two pedestrians i and j to stay away from each other. A_i and B_i are constants, $d_{ij} = |\mathbf{r}_i - \mathbf{r}_j|$ denotes the distance between the pedestrians' centres of mass, $r_{ij} = (r_i + r_j)$ is the sum of radii of two interacting pedestrians, and $\mathbf{n}_{ij} = (\mathbf{r}_i - \mathbf{r}_j)/d_{ij}$ is the normalised vector pointing from pedestrian j to i. The other terms $kg(r_{ij} - d_{ij})\mathbf{n}_{ij}$ and $\kappa g(r_{ij} - d_{ij})\Delta v_{ij}^t \mathbf{t}_{ij}$ constitute the normal and tangential contact forces resulting from physical interactions between agents touching each other. Here, k and κ represent constants, $\mathbf{t}_{ij}$ means the tangential direction, and $\Delta v_{ij}^t = (\mathbf{v}_j - \mathbf{v}_i) \cdot \mathbf{t}_{ij}$ is the tangential velocity difference. Function $g(x)$ ensures the contact forces are present only when agents touch each other and is defined as:

$$g(x) = \begin{cases} 0, & d_{ij} > r_{ij}, \\ x, & \text{otherwise.} \end{cases} \tag{3}$$

The interaction with walls is treated in a similar way, with d_{iW} meaning the shortest distance to wall W, $\mathbf{n}_{iW}$ denoting the direction normal to it, and $\mathbf{t}_{iW}$ the direction tangential to it:

$$\mathbf{f}_{iW} = \Big(A_i \exp\big((r_i - d_{iW})/B_i\big) = kg(r_i - d_{iW})\Big)\mathbf{n}_{iW} - \kappa g(r_i - d_{iW})(\mathbf{v}_i \cdot \mathbf{t}_{iW})\mathbf{t}_{iW}. \tag{4}$$

If a random pedestrian movement is to be introduced, a time-dependent fluctuation force $\boldsymbol{\xi}(t)$ could also be added to the right-hand side of Equation 1.

Moreover, in order to model panicking pedestrians getting impatient and pushy when they are stopped for too long, Helbing suggested increasing their desired speed according to:

$$v_i^0(t) = \big(1 - p_i(t)\big)v_i^0(0) + p_i(t)v_i^{\max}, \tag{5}$$

where $v_i^0(0)$ is the initial and $v_i^{\max}$ the maximum desired speed. The time-dependent parameter $p_i(t)$ measures the impatience and is defined as:

$$p_i(t) = 1 - \bar{v}_i(t)/v_i^0, \tag{6}$$

where $\bar{v}_i(t)$ denotes the average speed in the desired direction of motion of a particular agent. Defining the desired speed in such a way causes agents to get more aggressive the longer they have to wait, hence, producing a less efficient outflow owing to the "faster-is-slower-effect".

Additionally, Helbing attempted to model the herding/flocking behaviour observed in a situation when pedestrians are trying to exit a room with limited visibility and not knowing the locations of the exits. In his model, each pedestrian can either choose their individual direction $\mathbf{e}_i$ or follow the average direction $\langle \mathbf{e}_j^0(t) \rangle_i$ of their neighbours j in a certain radius, or try a mixture of both depending on an a parameter s_i:

$$\mathbf{e}_i^0(t) = \mathrm{Norm}\big((1 - s_i)\mathbf{e}_i + s_i \langle \mathbf{e}_j^0(t) \rangle_i\big), \tag{7}$$

where $\mathrm{Norm}(\mathbf{x}) = \mathbf{x}/|\mathbf{x}|$ is normalisation of a vector $\mathbf{x}$. Hence, low s_i means very individualistic behaviour and high s_i indicates flocking.

2.4.2 Changes and improvements proposed

A number of changes and improvements to the model have been proposed since the publication of Helbing's papers in 1995 and 2000 [15, 19]. The most important ones are presented below.

Circular and elliptical specifications First of all, two different specifications for the social repulsive component of the force have been proposed: circular (described in Section 2.4.1) and elliptical. The elliptical specification does not only depend on the distance d_{ij} but also on the relative velocity of interacting agents. This leads to the social repulsive force having a lateral component and leading to less confrontative and smoother evading manoeuvres [13].

Anisotropy Another proposed change to the social repulsive component of the force is the introduction of anisotropy which models the fact that pedestrians show less response to other pedestrians behind them [13]. This is done by multiplying the social repulsive force component by an angular-dependent factor to ensure that social forces in front of a given pedestrian have a stronger effect than the ones behind him.

Velocity dependence of pedestrian interaction forces According to Moussaid [20], the parameter B_i of the social component force should depend on relative velocities. As parameter B_i defines the interaction range between agents, it was noted that it should increase with higher relative speeds to reflect the fact that fast relative motions require evading decisions in a larger distance.

2.4.3 Criticism of the model

Helbing's social force model has been sometimes criticised for over-simplifying the problem. Lakoba [21] pointed out that the initial value for the interaction range parameter

$B_i = 0.08$ m proposed by Helbing [19] is too small as it results in unrealistically high accelerations and forces acting on interacting agents. Similar issue has been found with the interaction strength parameter initially proposed by Helbing ($A_i = 2000$ N) [22]. Owing to such a high value of A_i, humans are modelled as very stiff springs which again leads to unrealistically high forces acting on them. New parameters have been proposed together with an overlap eliminating algorithm to avoid spring-like modelling of pedestrians.

Furthermore, Zhao [23] investigated placing an obstacle in front of the exit to improve pedestrian outflow in panic situations. Using a calibrated (modified parameters) Helbing's social force model, he discovered that placing an obstacle did not reduce or absorb the pressure in the region of exit, which is contrary to Helbing's findings [2].

2.4.4 Importance of verification and validation

Helbing's social force model is highly dependent on many arbitrarily chosen parameters (A_i, B_i, k, κ, and others). It is generally a complex task to identify the values of those parameters in Helbing's or any other microscopic pedestrian model. This is mainly because a large number of them is not easy or ever possible to observe directly, and because few suitable data is available. To this date, there has not been a common standard procedure to verify and validate models for panic evacuations [18]. Many researchers who developed pedestrian models (including Helbing) expressed a need for good methods of evaluating simulations reliability.

Most often, the current practice is to validate the models against empirical data like video recordings of pedestrian traffic or emergency situations. It can also be done through controlled experiments which, however, can be limited due to ethical and methodological constraints. In order to investigate escape panic, experiments on animals like mice or ants have been performed too [24, 25]. An immense virtual environment was also analysed as a viable option for conducting crowd experiments with real people [26].

In this project, the mathematical models developed were rigorously tested against available data. Two appropriate data sets for calibration have been found. They include the classroom evacuation during an earthquake [3] and the theatre evacuation exercise [4].

2.5 The Station nightclub fire in 2003

The Station fire is the fourth-deadliest nightclub fire in the US history. In the aftermath, 100 people died and over 200 were injured. The causes and timeline of the accident are precisely described in the official National Institute of Standards and Technology (NIST) report [1]. The tragedy began when the performing band used pyrotechnics which started the fire inside the nightclub. This prompted all of around 420 people to evacuate, with most of them choosing the main exit as their destination. The narrow corridors and passages around the area caused blockages and panic within the crowd, which together with the smoke led to numerous casualties and injuries. It was estimated that the conditions inside the nightclub would have led to severe incapacitation or death within the first 90 s after the fire started.

Simulations concerning The Station nightclub have been conducted before by the official NIST team [1, 27] as well as other researchers [28, 29, 30] who combined agent-based modelling with detailed fire simulations to better understand the course of events. Commercial evacuation software packages like Simulex, buildingExodus or FDS+Evac were used in their research.

The official report from 2005 [1] names the top three largest contributors to the substantial loss of life in The Station to be:

- The presence of flammable and hazardous mix of materials in the nightclub.
- An inadequate capability to suppress the fire during its early stage of growth.
- The inability of the exits to handle all of the occupants in the short time available for such a fast growing fire.

The third bullet point was the focus of analysis in this project. The simulations used the calibrated model to analyse the agent flow rates and total evacuation times for different geometry setups around the lobby area, which was the main congestion point in the real evacuation.

3 Methodology

3.1 Description of the implemented model

The computer model of panic evacuations developed throughout the project was implemented in OpenFOAM, an open-source Computational Fluid Dynamics (CFD) software. Apart from CFD, OpenFOAM also allows for the development of customised numerical solvers. One of such frameworks capable of solving agent-based problems (agentFOAM) was used to apply the mathematical models, set up and run evacuation simulations. Standard C++ scripting was employed and simulations were always run in two dimensions (2D).

The following section aims to describe the most important mathematical models implemented in the code, the parameters used to control agents' behaviour and the process of solving the equations.

3.1.1 Agent forces

Agent-agent repulsion Helbing's social force model described in Section 2.4 was implemented for the agent-agent interaction:

$$\mathbf{f}_{ij} = \Big(A_i \exp\big((r_i + r_j - d_{ij})/B_i\big) = kg(r_{ij} - d_{ij})\Big)\mathbf{n}_{ij} + \kappa g(r_{ij} - d_{ij})\Delta v_{ij}^t \mathbf{t}_{ij}. \tag{8}$$

Although valeus of A_i and B_i might vary between individuals, one average parameter $A_i = A$ and one average parameter $B_i = B$ were used for all agents i to enable an easier calibration process. Parameters k and κ were treated similarly. The final model allowed for initialising agents as spheres (circles in 2D) with a normally distributed radii r_i specified by the user. Although other geometrical shapes could be used to describe pedestrians, spheres were preferred due to their ease of implementation.

A few optional changes were also added to the model. An anisotropy weighting parameter, based on Johansson's and Helbing's work [31], was applied:

$$w(\phi_{ij}) = \left(\lambda + (1-\lambda)\frac{1+\cos(\phi_{ij})}{2}\right), \tag{9}$$

where ϕ_{ij} is the angle between the direction of motion of agent i and the distance vector between agents i and j. The parameter w multiplies the social repulsive component of the

$\mathbf{f}_{ij}$ force to adjust its magnitude. The anisotropy parameter λ is specified by the user and controls how strongly w depends on angle ϕ_{ij}. Moreover, an option to linearly increase parameter B with an increase in agent's instantaneous speed was added. Although both of those optional changes were implemented in the code, anisotropy model and linear dependence of B on $\mathbf{v}_i$ were turned off for the final simulations. This is because they introduced extra parameters which made the calibration more difficult, and failed to yield better results.

Some aspects of Helbing's model described in Section 2.4 like the change of agent's desired speed depending on their panic parameter or herding/flocking behaviour, were not implemented in the final code. They were more complex and deemed not crucial for the project, and priority was given to the development of other algorithms like route choices. Despite this fact, the model was still capable of representing panic behaviour reasonably well as described later in the report.

Agent-walls repulsion Similarly, Helbing's social force was implemented for the repulsion of agents from walls (also called borders):

$$\mathbf{f}_{iW} = \Big(A_i \exp\big((r_i - d_{iW})/B_i\big) = k_W g(r_i - d_{iW})\Big)\mathbf{n}_{iW} - \kappa_W g(r_i - d_{iW})(\mathbf{v}_i \cdot \mathbf{t}_{iW})\mathbf{t}_{iW}. \quad (10)$$

It was decided that the parameters A_i, B_i, k_W and κ_W for the agent-walls repulsion will be set equal to the general parameters A, B, k and κ defined for the agent-agent interactions. Such approach agrees with Helbing's assumptions [19] and was done in order to further reduce the number of parameters needed to be calibrated.

A cutoff distance r_{cut} was also defined for the agents' interactions with borders. The importance of the parameter was realised during the verification and validation of the model as unusual behaviour of agents in narrow passages was discovered for large default cutoff distances. A diagram depicting the cutoff distance, and the agent-agent and agent-walls forces can be seen in Figure 5.

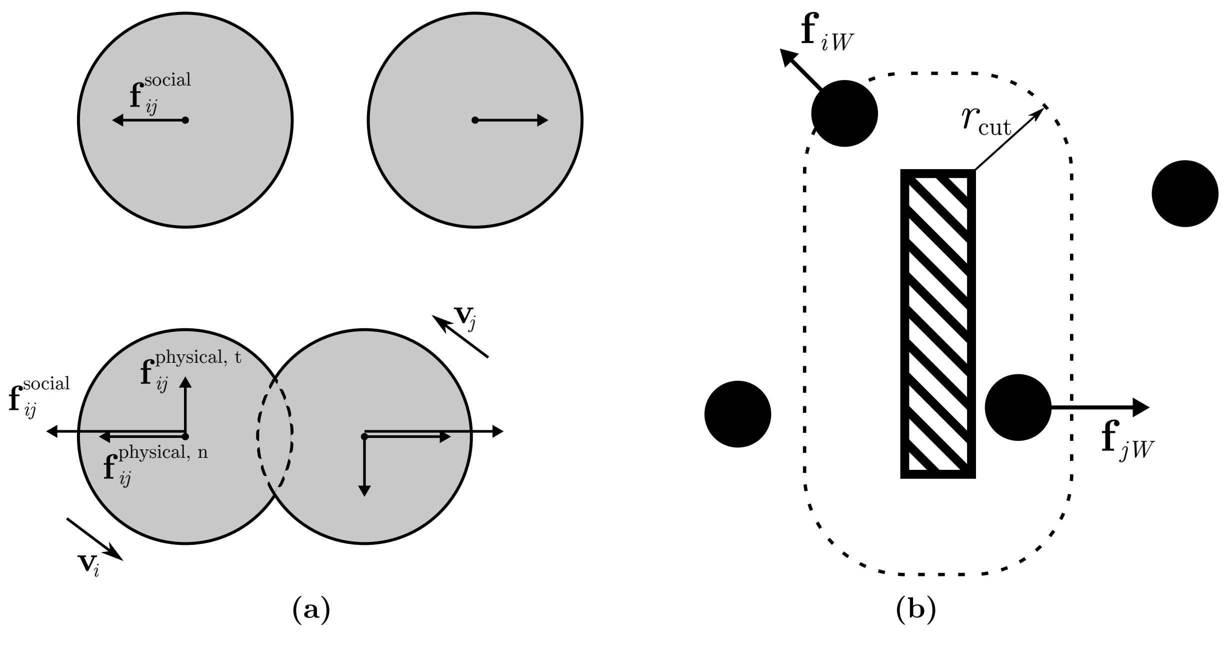


Figure 5: (a) Different components of the Helbing's social force $\mathbf{f}_{ij}$ for nonoverlapping and overlapping agents. (b) Agent-wall repulsion with the force cutoff distance marked.

Quadrilaterals were used to define walls in the code. Employing such a method was vital for implementing algorithms to find the closest distance between an agent and a wall or to set up agent scheduling. Round obstacles were discretised using a set of rectangles. In addition to the wall repulsion force, a reflection algorithm was also implemented to ensure agents would never get pushed across a border. If at any given time step, the position of an agent (their centre) happened to be inside a wall, that agent would have their position vector $\mathbf{r_i}$ shifted in the direction of outward-pointing normal of the border and velocity vector $\mathbf{v_i}$ reflected.

Fluctuations In order to introduce some natural random motion, a fluctuation force $\boldsymbol{\xi}(t)$ was added in the code. It also helps agents escape from any undesirable and rare force equilibrium situations. A user-defined parameter η describes the strength of $\boldsymbol{\xi}(t)$ in the simple model implemented:

$$\boldsymbol{\xi}(t) = \eta \begin{pmatrix} X \\ Y \end{pmatrix}, \tag{11}$$

where $X \sim \mathcal{N}(0,1)$ and $Y \sim \mathcal{N}(0,1)$ are random variables from a normal distribution with mean $\mu = 0$ and variance $\sigma^2 = 1$.

Free will The free will force implemented in the code took a similar form as described in Section 2.4:

$$\mathbf{f}_i^{\text{will}} = m_i \frac{v_i^0 \mathbf{e}_i^0(t) - \mathbf{v}_i(t)}{\tau_i}. \tag{12}$$

The value of relaxation time τ_i was taken from literature [19] to be 0.5 s. As the model describing the change of agent's desired speed depending on their panic parameter was not implemented, the desired speed v_i^0 was not a function of time. Similarly to an agent's mass m_i, it was specified by the user by declaring the mean and standard deviation for a normal distribution among the simulated agents. Finally, agent's desired direction of motion $\mathbf{e}_i^0$ depended on their scheduling described in the next section.

3.1.2 Agent scheduling

Most of the commercially available software uses shortest paths to determine the routes to be followed by evacuating agents [32]. Other interesting methods include, for example, obtaining a vector field as an approximate solution to a potential flow problem of a two-dimensional incompressible fluid flowing out of the domain. The field is then used as a space-dependent preferred walking direction for agents. Such approach is taken in the FDS+Evac package [33].

Distance map and vector field solutions usually require careful discretisation of simulation domain to store information about desired direction of motion in each mesh element separately. This information is then read by an agent occupying a given cell to assign them with the desired direction. Such approach was difficult to implement in the project due to the way borders were defined in the code, and because the meshing algorithm did not account for their presence. Therefore, focus was placed on developing a simpler algorithm and a graph-based solution.

Set of local goals The first path finding model implemented consisted of a set of local goals defined with boxes (rectangular patches in 2D). They were defined for each agent on an individual or group basis. The goals had to be reached in a specific order and none of them could have been skipped. The model calculated each agent's desired direction vector $\mathbf{e}_i^0$ from the agent's instantaneous position $\mathbf{r}_i$ and the centre of the box $\mathbf{c}_j$:

$$\mathbf{e}_i^0 = \mathrm{Norm}(\mathbf{c}_j - \mathbf{r}_i). \tag{13}$$

If at any time step, the agent's position was within the area of the rectangular patch j, their next destination would switch to box $j+1$ as shown in Figure 6. The process would repeat until the centre of the last box was reached.

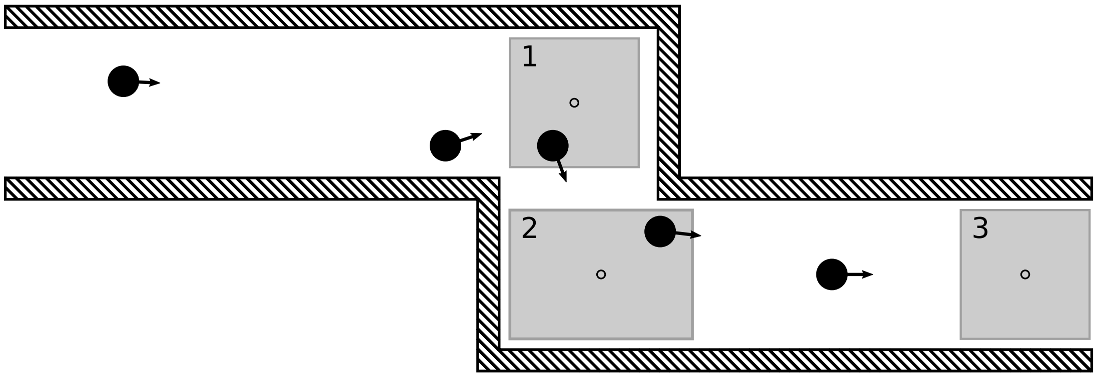
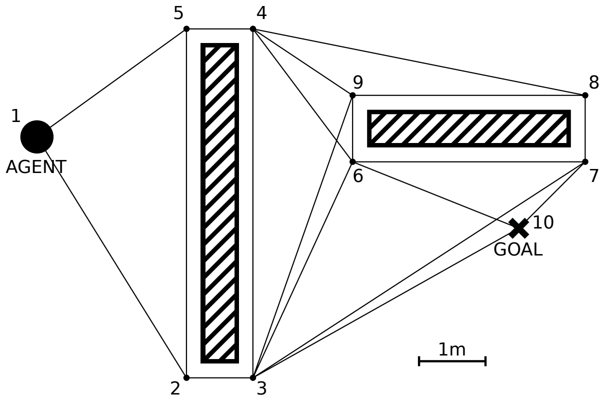


Figure 6: A series of local goals defined using boxes.

An apparent advantage of this method is good control over the paths agents take. Although tedious to define on per agent basis, the model allows them to follow precisely defined routes as observed during real evacuations (e.g. earthquake in Chinese high school [3]). The main disadvantage is the fact that routes are static and pre-defined. Hence, agents are unable to reach their local goals if obstacles are placed in between. This can theoretically be avoided by positioning local boxes in a smart way, however, in crowded systems, agents may still get pushed out of their way and end up trapped in front of walls. Moreover, defining coordinates of multiple boxes for numerous agents is time-consuming, prone to errors, and difficult to apply to large complex simulations. Hence, the visibility graph solution was also implemented.

Visibility graph and shortest path The need for a different agent scheduling model was motivated by the scale and complexity of the nightclub evacuation simulation. An algorithm capable of changing preferred routes dynamically depending on agents' positions was required. The visibility graph method was chosen as implementing it in the agentFOAM framework was feasible and because it allowed for finding the shortest paths to exits.

It can be proved that in a 2D domain with polygonal obstacles, the shortest path between any two points will always take a form of a finite chain of straight line segments [34]. An agent's position, their final goal and coordinates of borders vertices would determine such a route in this project's simulations. Hence, the first step in solving the problem was to find and map all sensible chains of line segments leading to the exit. This was done using a visibility graph described by an adjacency matrix as shown by the example in Figure 7.



$$\begin{pmatrix} 0 & 4.3 & 0 & 0 & 2.8 & 0 & 0 & 0 & 0 & 0 \\ 4.3 & 0 & 1.0 & 0 & 5.3 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1.0 & 0 & 5.3 & 0 & 3.6 & 6.0 & 0 & 4.5 & 4.6 \\ 0 & 0 & 5.3 & 0 & 1.0 & 2.5 & 0 & 5.1 & 1.8 & 0 \\ 2.8 & 5.3 & 0 & 1.0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 3.6 & 2.5 & 0 & 0 & 3.5 & 0 & 1.0 & 2.7 \\ 0 & 0 & 6.0 & 0 & 0 & 3.5 & 0 & 1.0 & 0 & 1.4 \\ 0 & 0 & 0 & 5.1 & 0 & 0 & 1.0 & 0 & 3.5 & 0 \\ 0 & 0 & 4.5 & 1.8 & 0 & 1.0 & 0 & 3.5 & 0 & 0 \\ 0 & 0 & 4.6 & 0 & 0 & 2.7 & 1.4 & 0 & 0 & 0 \end{pmatrix}$$

Figure 7: Visibility graph with ten nodes and the corresponding adjacency matrix storing information about the connectivity and distances between the nodes. The shortest path leads through nodes 1-5-4-6-10 and has a total distance of around 9 m.

Borders vertices were used to generate the nodes of the visibility graph. Those points were offset by the distance r_{offset} in the direction of the sum of normals of the corresponding edges. Similarly, perceived borders themselves were offset outwards for the purpose of the scheduling algorithm (not for the agent-wall interaction forces) by the same amount. This was done to account for agent sizes. The typical value of r_{offset} was equal to the maximum agent radius in a simulation.

Next, connectivity and distances between the nodes had to be calculated. Two nodes p_i and p_j were defined to be mutually visible if the line segment p_ip_j did not intersect any edges of the offset quadrilateral borders [34]. The corresponding distances between nodes p_i and p_j were then stored in the $(i,j)^{\text{th}}$ entry of the adjacency matrix. A zero value indicated no connectivity. As borders always remained fixed during the simulations, this step was performed only once.

On the other hand, agent positions and their final goals might have varied throughout simulations. Hence, the connectivity of the first and last nodes of the visibility graph were updated every time step. This provided agents with the necessary spatial awareness preventing them from ever getting stuck behind walls. However, the algorithm also significantly increased the computational time of the simulations.

Finally, the updated adjacency matrix was used as an input for Dijkstra's algorithm of finding the shortest paths between nodes in a graph [35]. The algorithm was chosen because of its relative efficiency, popularity and ease of application in the code. A number of online resources were used as an aid in implementing both the visibility graph and Dijkstra algorithm [36, 37, 38].

3.1.3 Velocity Verlet integration

The motion of each agent i in ABM simulations is described by Newton's equations of motion:

$$\mathbf{v}_i(t) = \frac{d\mathbf{r}_i(t)}{dt}, \tag{14}$$

$$m_i\mathbf{a}_i(t) = m_i\frac{d\mathbf{v}_i(t)}{dt} = \mathbf{f}_i(t). \tag{15}$$

The Veloctity Verlet technique was used to discretise those equations and update agent's velocities and positions. It proceeded as follows for one time step $t \to t + \Delta t$:

Step 1 Update half of the velocity of all agents in the system:

$$\mathbf{v}_i(t + \Delta t/2) = \mathbf{v}_i(t) + \frac{1}{2}\mathbf{a}_i(t)\Delta t. \tag{16}$$

Step 2 Move agents to their new position:

$$\mathbf{r}_i(t + \Delta t) = \mathbf{r}_i(t) + \mathbf{v}_i(t + \Delta t/2)\Delta t. \tag{17}$$

Step 3 Compute the net forces acting on all agents:

$$\mathbf{f}_i(t + \Delta t) = \mathbf{f}_i^{\text{will}} + \sum_{j(\neq i)} \mathbf{f}_{ij} + \sum_{W} \mathbf{f}_{iW} + \boldsymbol{\xi}. \tag{18}$$

The force components on the right-hand side are functions of agent's desired speed $\mathbf{e}_i^0(t)$, velocity $\mathbf{v}_i(t + \Delta t/2)$ and position $\mathbf{r}_i(t + \Delta t)$.

Step 4 Compute the new acceleration of all agents:

$$\mathbf{a}_i(t + \Delta t) = \frac{\mathbf{f}_i(t + \Delta t)}{m_i}. \tag{19}$$

Step 5 Update the second half of the velocity of all agents (due to the new acceleration):

$$\mathbf{v}_i(t + \Delta t) = \mathbf{v}_i(t + \Delta t/2) + \frac{1}{2}\mathbf{a}_i(t + \Delta t)\Delta t. \tag{20}$$

The choice of the time step is important in an ABM simulation mostly for its numerical stability. A reasonable value of $\Delta t = 0.01$ s was chosen for all the simulations. Such a low value prevented any excessive overlaps between agents and a possibility of agents passing through borders.

3.1.4 Other features

Another important model implemented in the code involved defining different types of domain boundary conditions (BC). When reaching the end of the domain, agents could be either reflected back inside (wall type BC), deleted from the simulation (deletion patch) or pass through one boundary side and reappear on the opposite side with the same velocity (periodic BC).

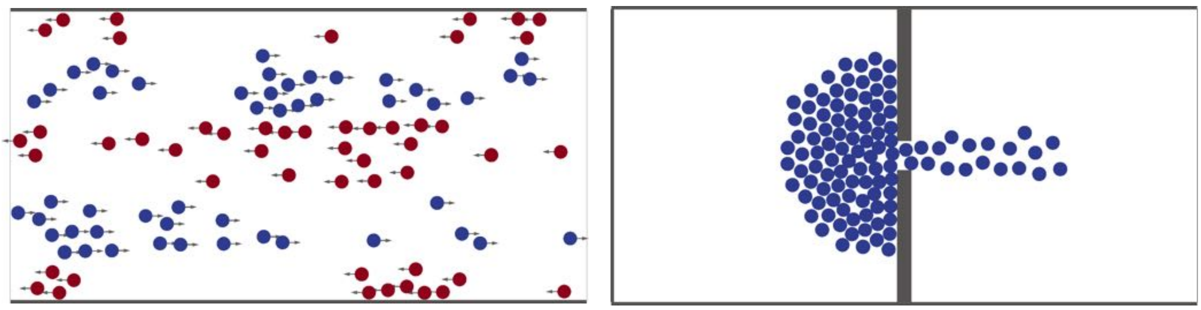
Moreover, different initialisation utilities were implemented. Agents could be placed in the domain randomly, uniformly within a box or by specifying their exact position coordinates. An initial delay could also be applied to provide them with the "reaction time". This was necessary for proper calibration using the classroom [3] and theatre [4] cases.

Finally, the code was capable of outputting various measurements like agent count, velocities, flow rates in a specified area or average densities.

3.2 Verification of the code

Verification can be defined as “the process of determining that a model implementation accurately represents the developer’s conceptual description of the model and the solution to the model” [18]. It can also be understood as checking whether the equations are solved correctly.

A series of experiments was developed to test different features of the code like agent-agent and agent-walls repulsion, fluctuation forces, anisotropy parameter or agent scheduling with local goals and visibility graph. With the aid of animations and visual judgement, a suitable fluctuation force parameter of $\eta = 10$ N was chosen during the procedure. Using Helbing’s and Molnar’s approach [15], the verification was also performed by simulating the self-organisation of collective phenomena of pedestrian behaviour like lane formation, arching (see Figure 8) or oscillations at bottlenecks. ”Freezing by heating” effect was not described as it required the fluctuation force magnitude to increase in time, which was not implemented in the code. Animations showing examples of different verification procedures can be seen in Appendix A.



(a) **(b)**

Figure 8: (a) Lane formation, and (b) arching observed in agentFOAM simulations.

3.3 Model calibration and validation

Validation procedure was the second method employed to assess the model authenticity. The goal was to evaluate the quality of the model and determine the degree to which it is an accurate representation of the real world [18]. In the case of a panic evacuation model, both qualitative and quantitative validation testing needed to be employed. The first one compares the results of the simulations against the expectations of human behaviour. It is subjective to some degree but important to ensure a program represents a realistic way of acting by the agents. The second focuses on comparisons against reliable data like real evacuations or controlled experiments. Measurements like evacuation time or people flow rates can be analysed. Such validation process was combined with a calibration procedure in the project. Chosen parameters of the social force model were varied until a desirable match was obtained between the simulations and experiments.

The social force model in agentFOAM was calibrated using two cases: a real evacuation of a classroom during an earthquake in China, and an evacuation experiment in a movie theatre. They were chosen as both offered detailed data about number of people evacuated in time and the geometry of the environment. Information about initial distribution of people, their reaction delay and path selection was also available from camera footage. Having this data minimised the effect of agent scheduling on the simulation uncertainty and allowed for focusing on calibrating only the social force parameters.

3.3.1 Real evacuation in a Chinese high school

The earthquake occurred on April 20, 2013 with the epicentre in Ya'an, China. After it passed, a recording of classroom evacuation of Mingshan high school in the earthquake was broadcasted by CCTV-News. The video recording, which can be accessed online at https://youtu.be/G5H_ylTY0N4, provided detailed information about student initial positions, reaction times and route choices. The exact values of initial delays and the classroom geometry were found in Li's work [3]. In total, 65 students and one teacher managed to leave the classroom within 36 s. Because the event provided a rare source of real-life panic evacuation data, it was used as the first and main case for calibrating and validating the numerical model.

The classroom dimensions, single desk size and the door width were found in the literature to be 6.6 m × 9 m, 0.55 m × 0.42 m, and 1 m respectively [3]. Other dimensions, initial agent positions and their delays were obtained using the diagrams in scale provided by Li (see Figure 9a and Figure 9b). Agent scheduling was defined using a set of local

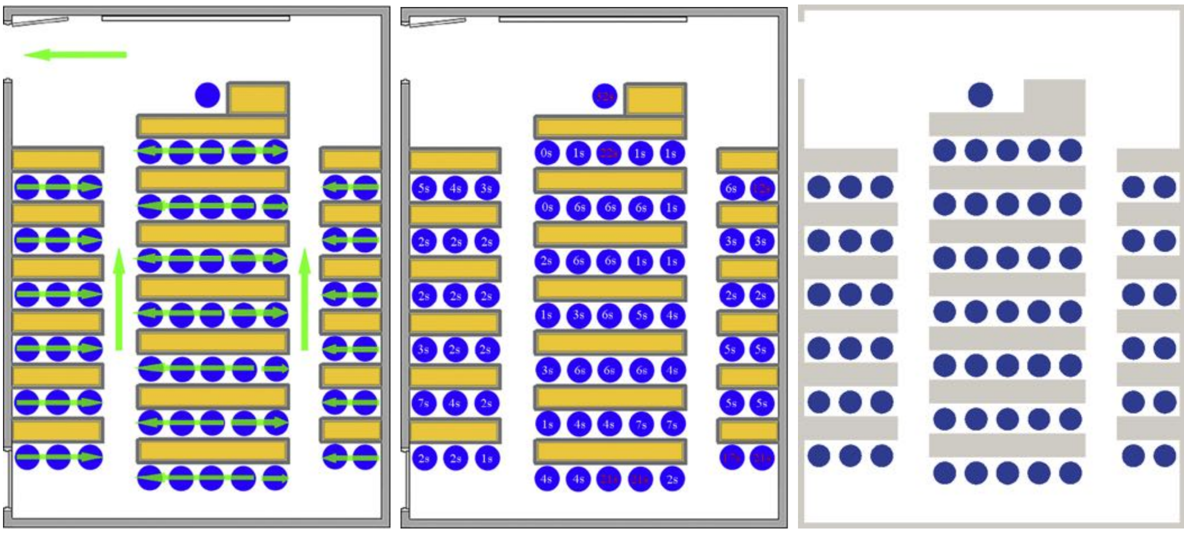


Figure 9: (a) Paths taken by students to the exit. (b) Students' initial reaction times. (c) A capture of the geometry and agents initialised in agentFOAM.

goals on per agent basis. This method was required to ensure agents in the simulation followed paths observed in the real evacuation video. Care was taken to specify boxes with the right dimensions (e.g. taking total width of passage between desks). They were also separated by small distances, which ensured agents were always close to their next local goal, and hence, trapping likeliness was reduced. A box measuring the cumulative number of people escaping the classroom was placed right outside the door.

A total of 11 parameters (excluding the deviations of normal distributions) needed to be set for the social force model implemented. As calibration with such a big number of variables would be virtually impossible, some of them were obtained from literature as summarised in Table 1. Agent masses and radii are the physical characteristics of the social group being analysed and it was reasonable to take those values as given. Moreover, four standard deviations 4σ for normal distribution of masses, radii and desired speeds were set to 10 kg, 0.01 m and 0.1 m/s respectively. Such approach was taken to introduce additional variability in the simulations and ensured that 99.99% of agents had their masses, radii and desired speeds within the specified ranges. As normal and tangential

Parameter	Value	Source
Mean agent mass (m_i)	58 kg	Literature [3]
Mean agent radius (r_i)	0.2 m	Literature [3]
Normal physical force (k)	819.6 kg/s	Literature [3]
Tangential physical force (κ)	510.49 kg/(ms)	Literature [3]
Relaxation time (τ_i)	0.5 s	Literature [19]
Fluctuation strength (η)	10 N	Verification procedure
Maximum allowable speed ($v_{\max}$)	equal to $v_i^0 + 0.1$	Dependent on v_i^0
Social force strength (A_i)	?	Calibration
Social force interaction (B_i)	?	Calibration
Mean desired speed (v_i^0)	?	Calibration
Agent-walls cutoff (r_{cut})	?	Calibration

Table 1: Social force parameters used in the classroom evacuation simulation.

physical force parameters k and κ affect the agents only in highly packed crowds and their general effect on simulation results was observed to be low, their values were again obtained from literature. Similarly, the relaxation time value of $\tau_i = 0.5$ s was used. For further simplification, the hard limit for the maximum allowable speed $v_{\max}$ was always set dependent on the value of desired speed: $v_{\max} = v_i^0 + 0.1$.

It was observed during test runs that parameters A_i, B_i, v_i^0 and r_{cut} had the biggest effect on both qualitative (expected human behaviour) and quantitative (evacuation time, flow rates) aspects of the simulations. Hence, the calibration procedure was performed on those parameters. Different combinations of values from ranges of $100 \leq A_i \leq 2000$, $0.01 \leq B_i \leq 0.2$, $0.4 \leq v_i^0 \leq 4.4$, and $0.11 \leq r_{\text{cut}} \leq 0.47$ were investigated. In each trial run, animations were used to analyse agent behaviour, and the simulation evacuation data was compared to the number of people evacuated in time during the real event.

3.3.2 Movie theatre evacuation exercise

In order, to confirm the parameters obtained with the classroom case, another validation based on a movie theatre evacuation exercise [4] was performed. In this case, all participants were informed about the nature of the experiment beforehand and urged to act carefully to avoid injuries. At the beginning of the movie show, the alarm went off and the evacuation began. The name and location of the venue were not specified in the literature, however, the geometry of the building was provided as seen in Figure 10. The initial positions of the people and their exit choices were known. In total, 101 university students took part in the exercise. To account for a different social group, the agent mean mass and radius were changed to 70 kg and 0.24 m respectively. Most of other parameters (obtained from both literature and classroom calibration) were kept the same. Two exceptions were the cutoff distance r_{cut} and the desired speed v_i^0 which was again varied to achieve a suitable match in terms of the number of evacuated people in time between the simulation and the experiment. The local goals agent scheduling was used. Boxes measuring the cumulative number of people escaping the theatre were placed for both front and rear routes in the locations where the experimental data was recorded (street and parking garage just outside of the building) [4].

3.4 Investigation of The Station nightclub evacuation

Having calibrated the numerical model, simulations of the evacuation of The Station nightclub were run. Information about the building geometry, tragedy timeline and ap-

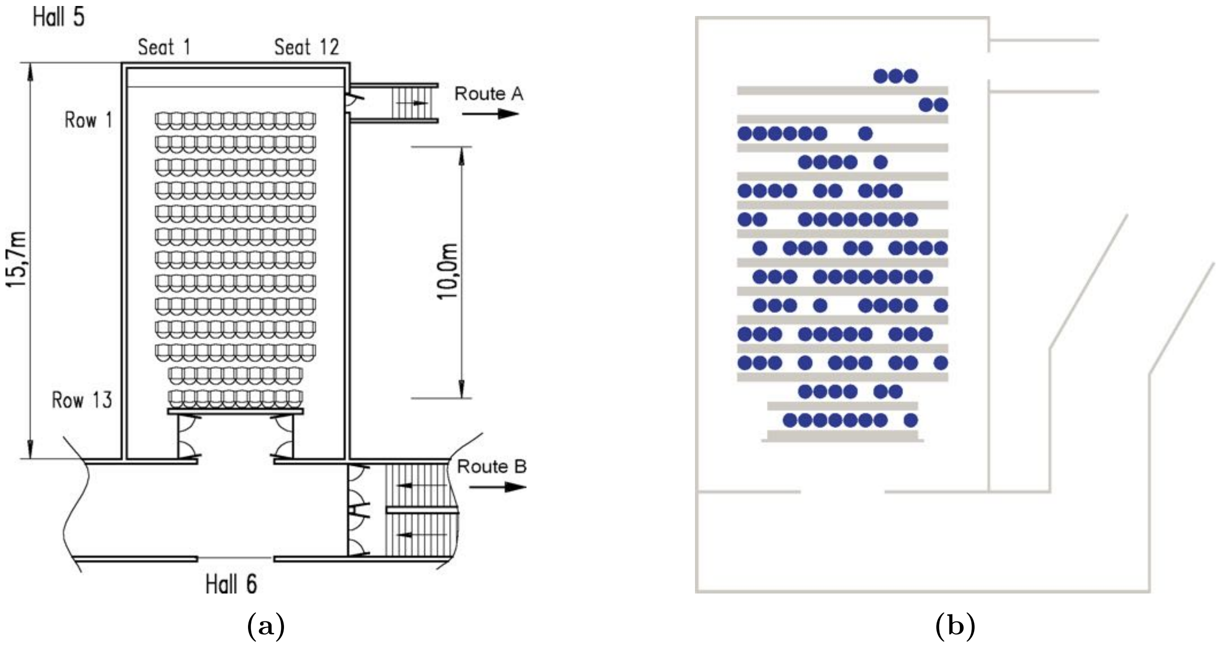


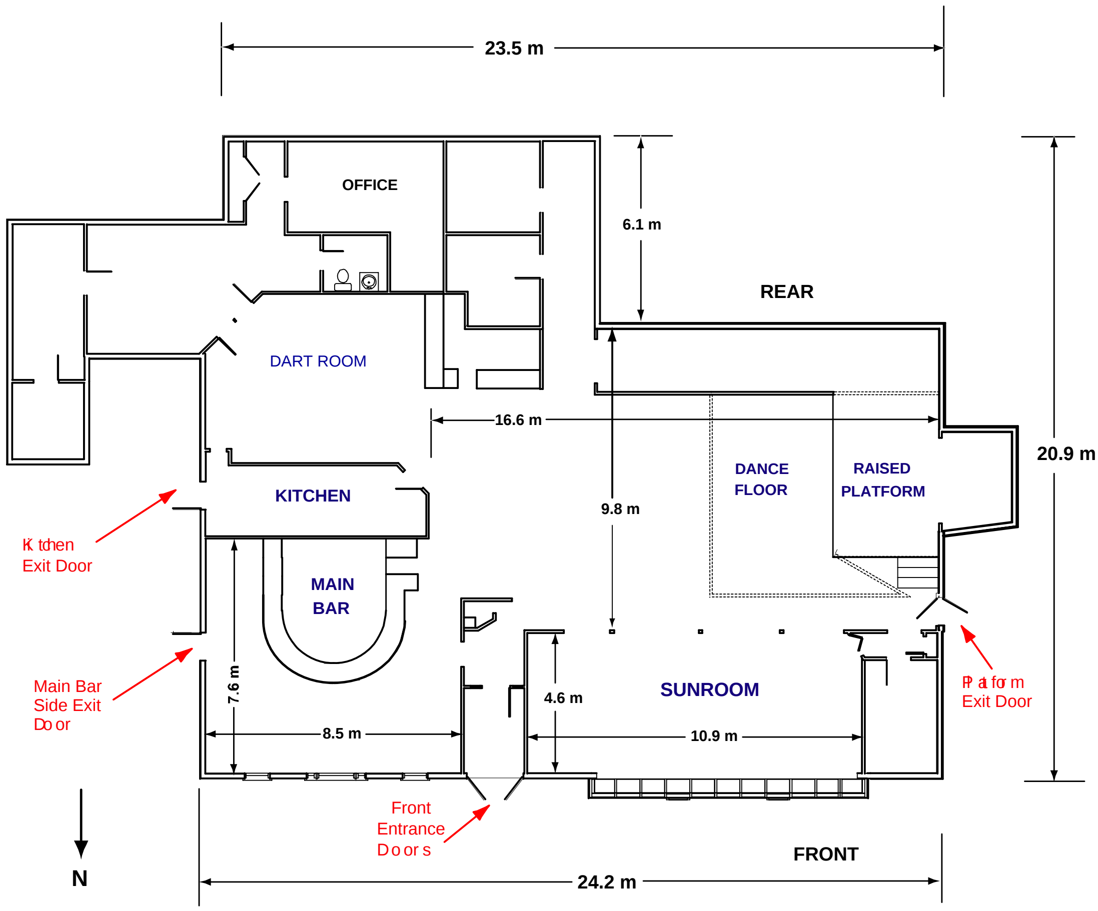
Figure 10: (a) Diagram of the theatre building [4]. (b) Theatre geometry and agents initialised in agentFOAM.

proximate number of people involved were obtained from the technical NIST report [1]. As the agentFOAM model was not capable of simulating the fire spread, only the evacuation was considered.

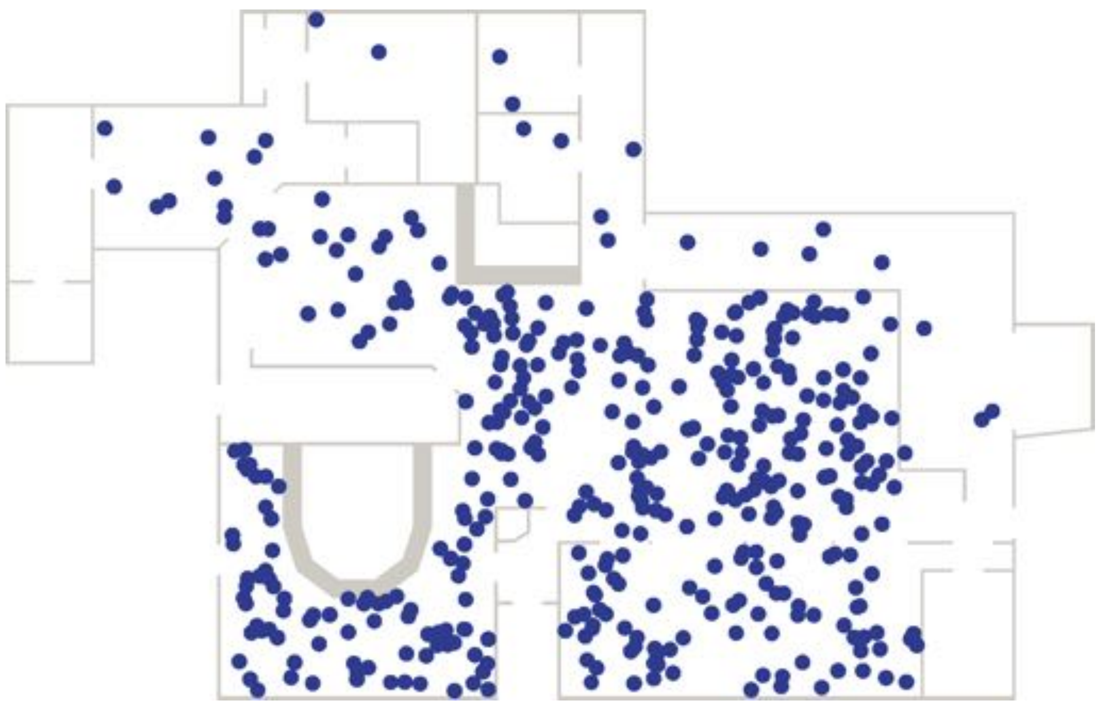
First, the data from the official report was used to estimate the percentage of people using each of the four exits available. It was concluded that out of 420 men and women present inside the nightclub, 93 chose the bar exit (22%), 20 chose the kitchen exit (5%), 30 chose the platform exit (7%) and 277 attempted to escape through the main door (66%). Such a distribution was dictated mainly by the general lack of knowledge about exits other that the most popular main door. The values above were used when defining the final goals of agents using the visibility graph method of path finding.

No data was avaialable about the exact distribution of people just before the fire started, but it was assumed that most were watching the show in front of the stage on the dance floor. People's exit choices, survivor reports and simulations performed by the official NIST team investigating the tragedy [1] were used to distribute the agents in agentFOAM. In the end, they were initialised randomly within 14 rectangular patches defined in the main bar, sunroom, dart room, and other areas of the nightclub as seen in Figure 11. Basing on the findings of the NIST report, an initial delay uniformly distributed between 24 s and 30 s was applied to all the agents. Zero time corresponded to the start of the fire in the venue.

Three separate analysis were conducted. The first one considered an unaltered geometry of the building in order to identify the main bottleneck which was expected to be around the vestibule door. Next, the geometry in the main exit area was changed in an attempt to improve the outflow of people. First, a simulation was run with the lobby walls removed, and secondly, both the lobby walls and walls surrounding the ticket-taker desk were deleted. The effects of those changes were quantified by measuring the cumulative number of agents escaped in time and the agent flow rates. The number of people remaining inside the nightclub after 90 s was also critical as, according to the NIST report, being inside after that time would have led to severe incapacitation or death.



(a)



(b)

Figure 11: (a) Plan view of The Station showing different rooms and exits [1]. (b) Geometry and agents initialised in agentFOAM simulations.

4 Results and Discussion

4.1 Validation cases

4.1.1 Classroom evacuation

The parameters A_i, B_i, v_i^0, and r_{cut} are highly correlated with each other, and ideally, they should be calibrated all together using mathematical optimisation algorithms [3]. Such approach was difficult to implement due to the time constraints of the project, and a literature-based trial and error method was used instead. The final set of parameters yielding best qualitative and quantitative results was found to be $A_i = 500$ N, $B_i = 0.04$ m, $v_i^0 = 1.4$ m/s, and $r_{\mathrm{cut}} = 0.21$ m. The simulated total evacuation time was 34.94 s, compared to around 36 s in the real event. The still images of the final simulation and the real evacuation can be seen in Figure 12 and the links to the videos are provided in Appendix A.

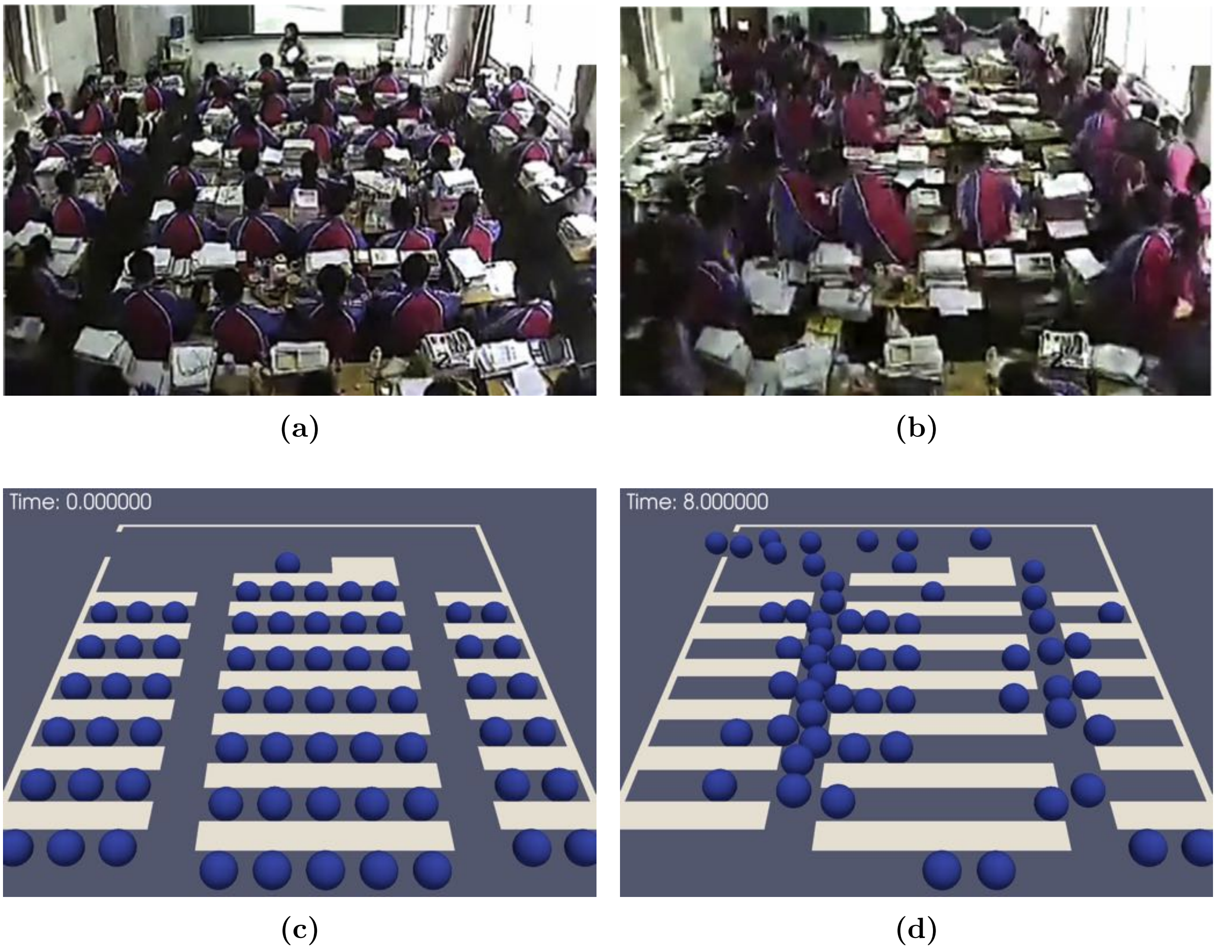


Figure 12: Actual and simulated pedestrian distribution during the earthquake evacuation. (a) Real footage, 0 s. (b) Real footage, 8 s. (c) Simulation, 0 s. (d) Simulation, 8 s.

The quantitative validation process was based on comparing the simulated evacuation curve (number of students who escaped in time) with the real one obtained from Li's analysis of the classroom camera footage [3]. The Euclidean Relative Difference (ERD) equation was employed to evaluate the average difference between experimental data (E_t)

and the model data (m_t) [18]:

$$\mathrm{ERD} = \frac{||E-m||}{||E||} = \frac{\sqrt{\sum_{t=0}^{t=T}(E_t-m_t)^2}}{\sqrt{\sum_{t=0}^{t=T}E_t^2}}, \tag{21}$$

where T is the total evacuation time and t is assumed to be a non-negative integer $t = 0, 1, 2, ..., T$. If two curves are identical in magnitude, Equation 21 should return a value of 0. The ERD value (expressed as a percentage) obtained with the final set of parameters was equal to ERD = 3.84%.

It is important to mention that the sets of parameters which produced quantitative results closest to reality were not necessarily the best in terms of the qualitative observations. Evacuation curves for which slightly lower ERD values were obtained, exhibited highly unrealistic human behaviour like strong bouncing effect of people interacting with borders (desks) in the narrow passages. A balance between quantitative and qualitative results was needed for the final set of parameters to ensure both represent reality reasonably well.

In addition to the real evacuation data, the final simulation was also contrasted with the results obtained in agentFOAM using parameters proposed by Helbing [19] and Li [3], as seen in Figure 13. Neither of them managed to yield satisfactory results. The high

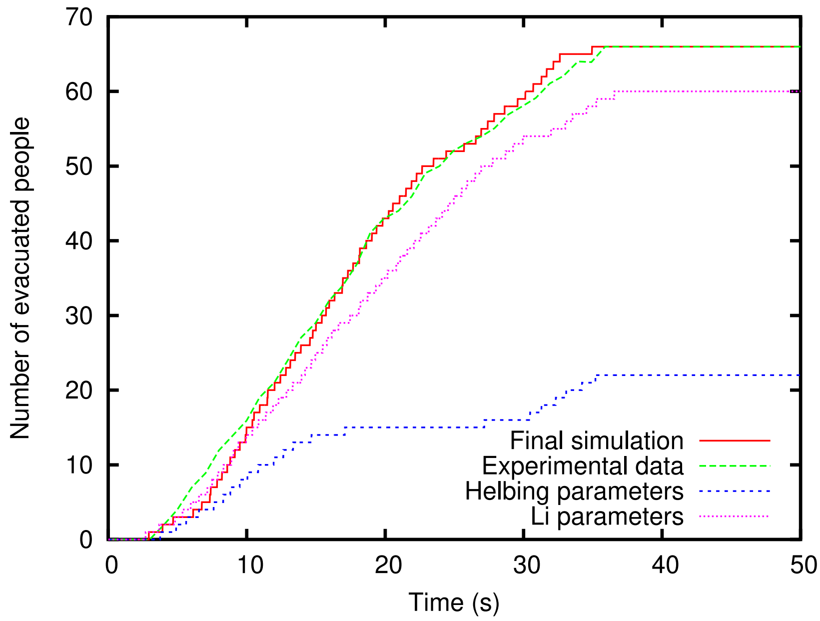
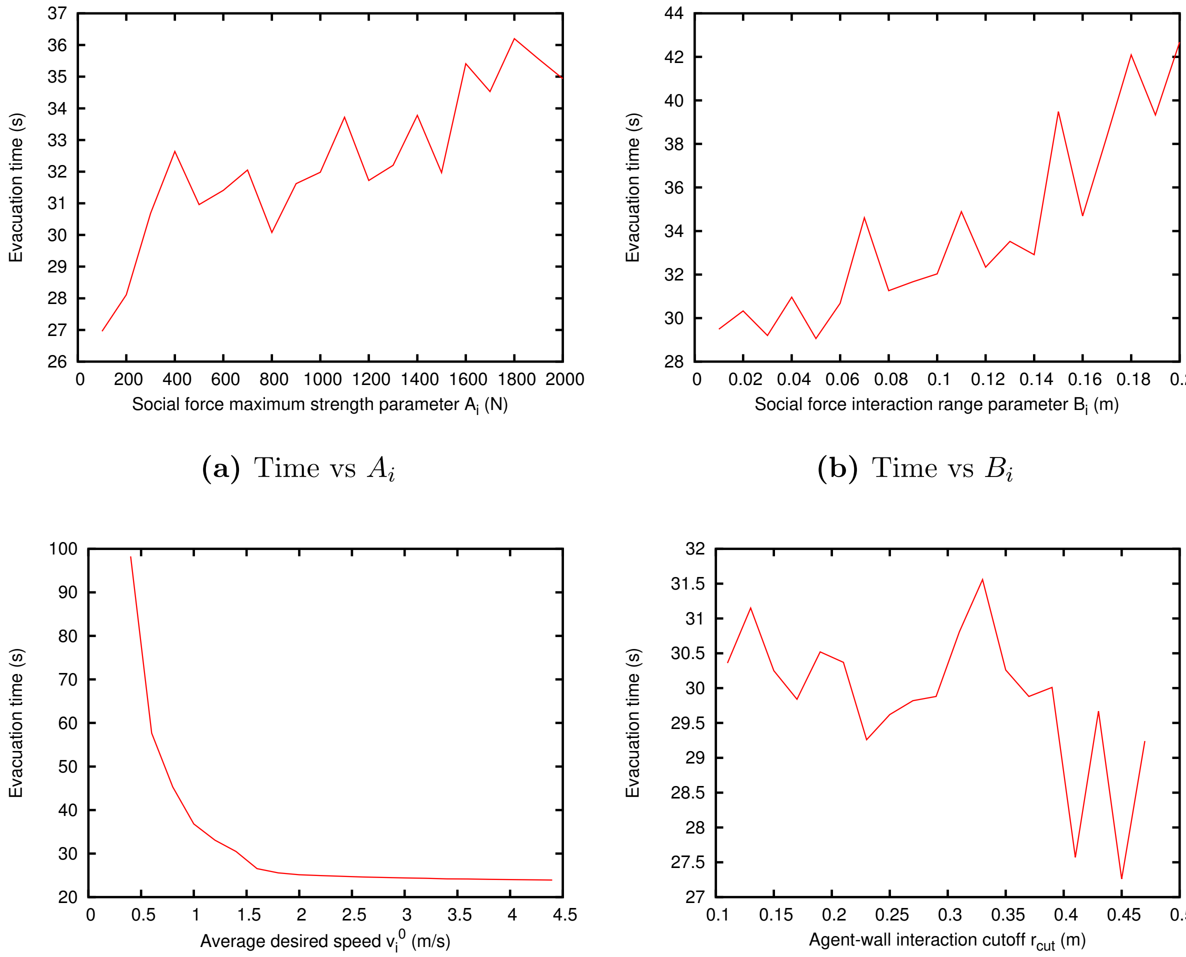


Figure 13: Classroom video data and evacuation curves for simulations using Helbing's parameters, Li's parameters, and the final set of calibrated parameters.

values of $A_i = 2000$ N and $B_i = 0.08$ m used by Helbing resulted in agents standing and moving at very big distances from each other. Such approach would probably be more suited to less dense and open space pedestrian situations. Moreover, Helbing did not specify any agent-walls cutoff distance r_{cut} (it was assumed to be a very large number in agentFOAM simulations), which was deemed crucial to limit agents' interactions to only the closest borders and prevent unrealistic bouncing behaviour in narrow passages. Although Li's parameters ($A_i = 998.97$ N and $B_i = 0.08$ m) produced more realistic results, their deviation from the experimental data was still significant. This might again be due to the same reasons - high values of A_i and B_i, and an almost-infinite cutoff distance r_{cut}. Using both Helbing's and Li's parameters in agentFOAM also resulted in some of the agents getting stuck in narrow passages between desks. This suggested that the implemented algorithm used to determine which borders agents should interact with might have been slightly different from the one used by Helbing and Li.

The dependence of the total classroom evacuation time on each of the calibrated parameters has also been analysed and is illustrated in Figure 14. In order to obtain



(a) Time vs A_i

(b) Time vs B_i

(c) Time vs v_i^0

(d) Time vs r_{cut}

Figure 14: Dependence of the total evacuation time on various social force parameters.

the graphs, each parameter was varied while all the others were held constant at their calibrated values. In order to avoid inconsistency across different measurements, the data presented ignores the evacuations of four agents assigned with highest initial delays. In such a scenario, the total evacuation time of 62 students observed in the real earthquake video was 32.89 s. First of all, it can be seen that higher maximum social force strength and higher interaction range tend to increase the total evacuation time of agents. This is consistent with the results obtained using Helbing's and Li's parameters. The evacuation time is also observed to be sensitive to changes in the average desired speed of agents up to around 1.6 m/s. On the other hand, no strong dependence of evacuation time on r_{cut} is seen in Figure 14d. However, the cutoff strongly affected the qualitative results of the simulations. For r_{cut} below the maximum agent redius, some agents ended up overlapping with the borders, while for high values, the "bounciness" effect was observed. In order to solve the issue, the r_{cut} value was always set equal to the maximum agent radius in a given simulation, which was $r_{\text{cut}} = 0.21$ m for the classroom case.

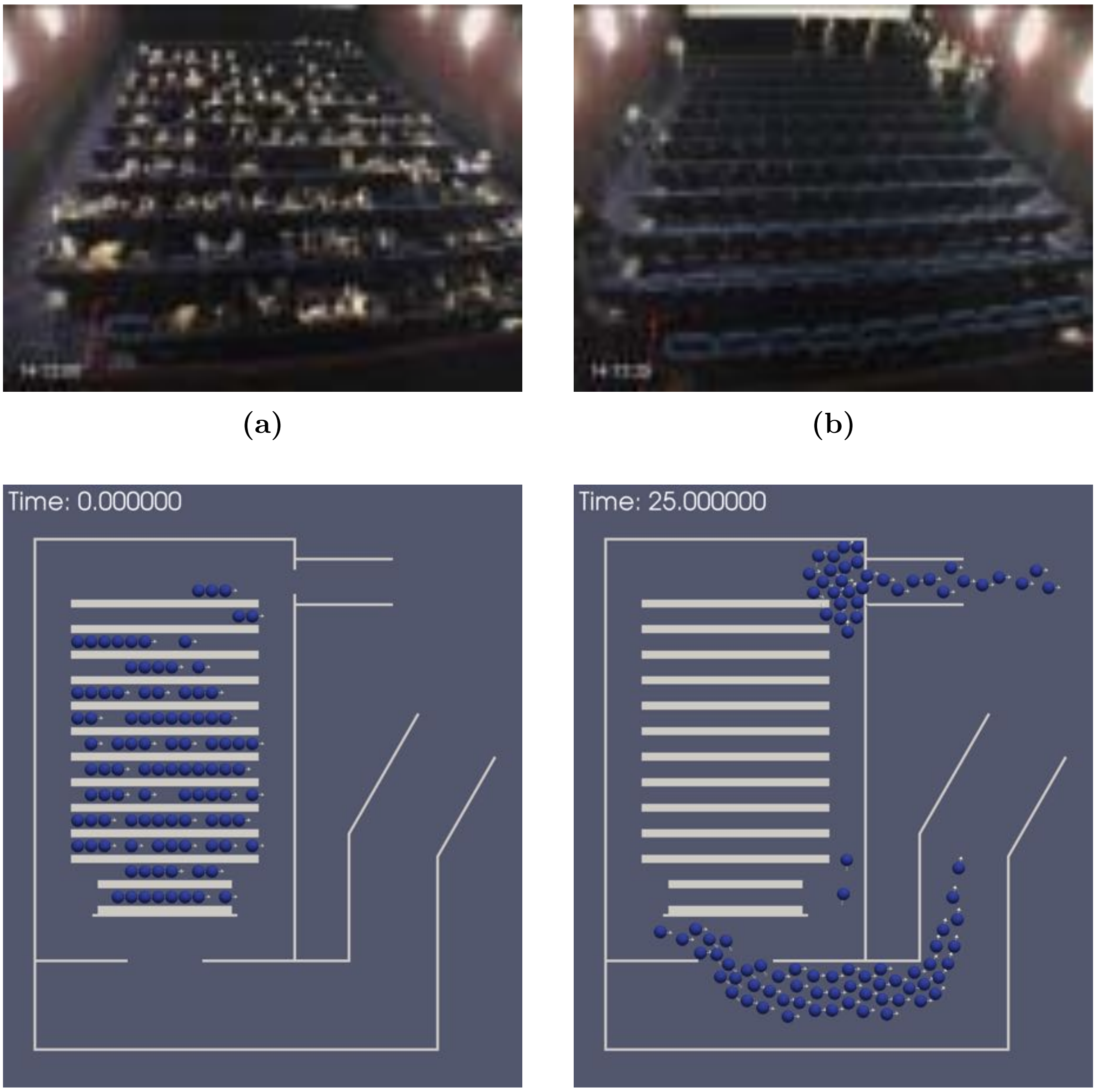
It was also noticed that the equations implemented in the code were unable to represent some of the phenomena observed in the real evacuation video. When escaping from the classroom, students highly varied their desired speeds over time. This was most likely due to their hesitation between evacuating and hiding under desks to seek safety. Such a complex human behaviour could not be modelled with Helbing's social force which instead focuses on averaging the crowd properties and assigning them to individuals in order to reproduce the final collective behaviour. Another qualitative shortcoming involved agents bouncing back and forward when waiting to squeeze inside the group of students moving up the classroom through the passage between desks. It was observed that the agent-agent "bounciness" could have been reduced using the anisotropy models, however, such changes also resulted in jamming and poorer quantitative results, and hence, were not implemented.

4.1.2 Theatre evacuation

The second validation step involved testing the classroom-calibrated parameters on the movie theatre evacuation exercise and adjusting the values of desired speed and cutoff distance to match the experimental data. Those parameters were deemed intrinsic to the social group and the evacuation situation being analysed and needed to be adjusted. The cutoff distance was set to $r_{\text{cut}} = 0.25$ m which corresponded to the maximum agent radius in the simulation and the best performing value of mean desired speed was found to be $v_i^0 = 0.75$ m/s. The maximum allowable speed was kept at the same value obtained for the classroom case: $v_{\max} = 1.5$ m/s. It was also assumed that the nature of interactions between agents would not change from the classroom case and same parameters A_i and B_i would describe them successfully. The still images of the final theatre simulation and the exercise can be seen in Figure 15 and the link to the simulation video is provided in Appendix A. The real footage shows the main theatre room with the screen located at the upper side of the image. The front exit is located in the upper right corner. Only low quality images were available as the exercise was conducted before 2003. A full video of the theatre evacuation experiment could not be obtained.

As seen in Figure 15, the simulations successfully reproduced the queuing effect at the front exit of the cinema. No visual data were available to assess the qualitative simulation results at the rear exit. Although the initial positions and exit choices of each of the agents were known [4], their exact paths (taking left or right corridor) had to be assumed and defined with the local goal boxes. Although low, the final value of desired speed $v_i^0 = 0.75$ m/s $= 2.7$ km/h was also deemed reasonable considering the facts that the exercise was not a real evacuation event and that students were asked to act carefully and calmly before the experiment.

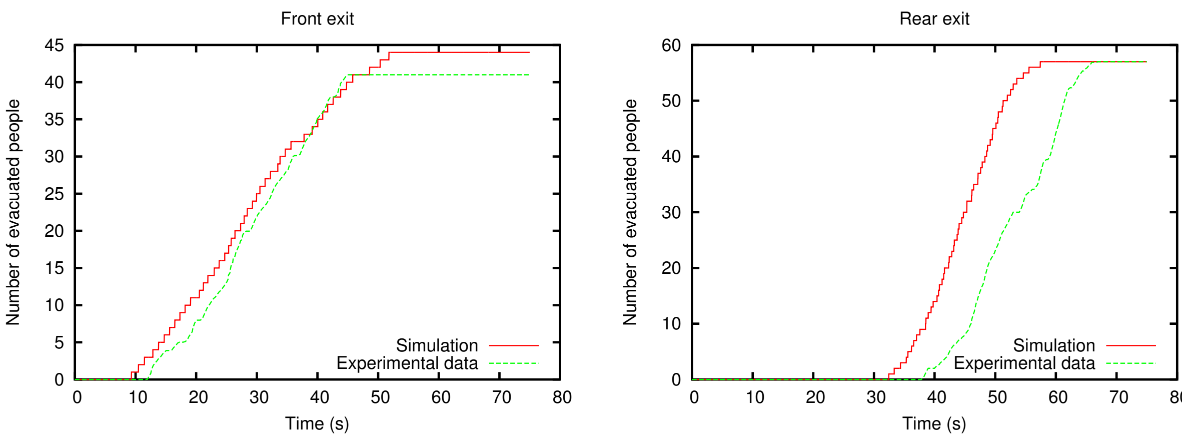
In terms of quantitative results, one of the main shortcomings of the experimental data available was the fact that four of all the participating students were not provided an identification hat. Hence, they were not accounted for in the number of people evacuated in time. The simulation and experiment evacuation curves for both the front and rear exit are provided in Figure 16. The EDR values for the front and rear exit evacuations are 11.25% and 50.30% respectively. It is clear that the calibrated parameters performed much better at reproducing the egress through the front escape route which consisted of a single 0.9 m wide door. The most likely explanation is that the front exit evacuation



(a) (b)

(c) (d)

Figure 15: Actual and simulated pedestrian distribution during the theatre evacuation. (a) Real footage, 0 s. (b) Real footage, 25 s. (c) Simulation, 0 s. (d) Simulation, 25 s.



(a) (b)

Figure 16: Simulation and experimental evacuation data for both (a) front and (b) rear theatre exits.

scenario had similar characteristics to the classroom case on which the calibration of A_i and B_i parameters was based. The resemblance of the two can be seen in terms of crowd densities (queuing in front of the door) and borders geometry (narrow passages). On the other hand, the wider rear exit and the long corridor leading to the parking garage are examples of less dense and open space pedestrian situations where people usually travel at bigger distances from each other and no queuing is observed. Low values of parameters A_i and B_i were not representative of such interactions and, hence, led to a significant underestimation of the egress time through the rear exit. Attempting to increase those parameters resulted in poorer qualitative results and an overestimation of the front exit egress.

4.1.3 Comments on calibration and validation

To date, there has not been a common standard procedure to perform verification and validation (V&V), and according to Cuesta [18], some crowd dynamics models still neglect this systematic process. This is because the pedestrian crowds and flow conditions vary significantly under different situations, and because it is very difficult to obtain systematic empirical data for model calibration. However, the V&V methods are still crucial to evaluate model authenticity and define its scope of application.

In this project, the best quality empirical data found was used in the calibration procedure. It allowed for systematic testing of both qualitative and quantitative results of the simulations. It has also been demonstrated that using a full set of parameters provided in literature [19, 3] is not enough to produce a successful outcome.

The method of obtaining the values of less crucial variables from literature and calibrating the four parameters A_i, B_i, v_i^0, and r_{cut} turned out to be a good approach as it correctly represented the behaviour of high-density crowds escaping through narrow passages. Less accurate quantitative results were obtained for the wider theatre exit suggesting that evacuations of different nature need be be described by different sets of parameters when using the social force model implemented in agentFOAM. However, as the nightclub tragedy was a high-density crowd situation, the parameters obtained during the calibration were deemed suitable to investigate the evacuation.

4.2 Nightclub evacuation

The final set of parameters used to simulate The Station evacuation is given in Table 2. As the event was a real panic evacuation, similar in nature to the classroom case analysed in Section 4.1, the classroom-calibrated mean desired speed value of $v_i^0 = 1.4$ m/s was used. As the population inside the nightclub consisted mainly of young adults [1], the mean agent radii r_i and masses m_i were given same values as in the theatre exercise in which university students took part. The offset distance value used for the visibility graph algorithm was equal to $r_{\text{offset}} = 0.25$ m. The other parameters were, as previously, based on the literature sources and calibration.

Due to the inability of agentFOAM to incorporate the effect of fire in the simulations, an ideal evacuation scenario was analysed. The aim was to investigate what would be the minimum time in which people could evacuate the building. The effects of changing the main exit geometry were also analysed. According to the NIST technical report [1], everybody needed to be evacuated within the first 90s of the simulation, in order to ensure that no fatalities or injuries occur.

Parameter	Value	Normal distribution deviation (4σ)
Mean agent mass (m_i)	70 kg	10 kg
Mean agent radius (r_i)	0.24 m	0.01 m
Normal physical force (k)	819.6 kg/s	-
Tangential physical force (κ)	510.49 kg/(ms)	-
Relaxation time (τ_i)	0.5 s	-
Fluctuation strength (η)	10 N	-
Maximum allowable speed ($v_{\max}$)	1.5 m/s	-
Social force strength (A_i)	500 N	-
Social force interaction (B_i)	0.04 m	-
Mean desired speed (v_i^0)	1.4 m/s	0.1 m/s
Agent-walls cutoff (r_{cut})	0.25 m	-
Visibility graph offset distance (r_{offset})	0.25 m	-

Table 2: Social force parameters used in the nightclub evacuation simulations.

4.2.1 Original building geometry

The first case considered the unaltered geometry of The Station nightclub. The results are visualised in Figure 17. The simulation confirmed that the main bottleneck in the evacuation procedure was the single door located in the vestibule area. This agreed with the findings of the official NIST report.

The visibility graph method of path finding (which was not used in the previous validation cases) managed to produce good qualitative results. The agents had their final goals defined outside of the building and nearby the exits. Having that information, they were capable of finding the respective shortest paths. The scheduling did not cause any undesirable and unrealistic trapping of agents between the borders. The simulation results showed that all the people managed to evacuate the building successfully in a total time of 134.62 s. The evacuation curves for all four exits are shown in Figure 18. It can be seen that more people evacuated through the main exit (283) and less people evacuated through the platform exit (24), when comparing to the initial estimations and the agent scheduling definition (277 and 30 respectively). This is due to the fact that six of the agents striving to use the platform door got carried by the crowd towards the vestibule area, where the the visibility graph algorithm changed their path to lead through the main exit.

It is clear that, even in an ideal scenario, the total evacuation time obtained in the simulation is significantly above 90 s. This confirms that the internal design of The Station building was one of the reasons behind the numerous fatalities and injuries during the fire. At 90 s, there were still 101 agents present inside the building. In an attempt to reduce the total evacuation time, different modification to the main exit geometry were analysed.

4.2.2 Modifications around the main exit

The first modification removed the vestibule walls which were the source of the initial bottleneck in the simulated evacuation. The second further deleted the ticket-taker desk and the surrounding walls. Although only the main exit was the area of focus, full scale simulations were run to ensure bottlenecks in other locations did not slow down the total evacuation of the building. The visual results of the geometry changes can be seen in Figure 19. The transition between the slow moving (blue coloured) and fast moving (red coloured) agents suggests where the bottlenecks are located. After the removal of

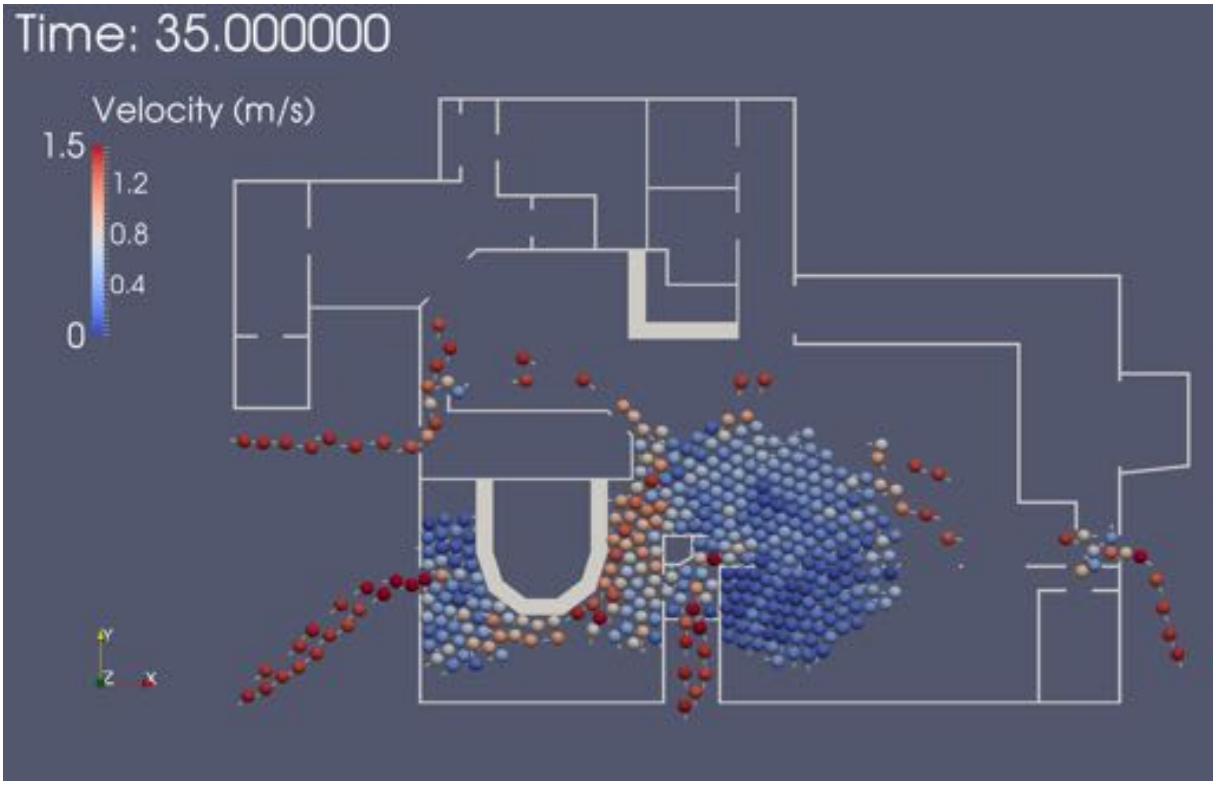


Figure 17: Simulation of the evacuation from The Station showing the first escaping agents.

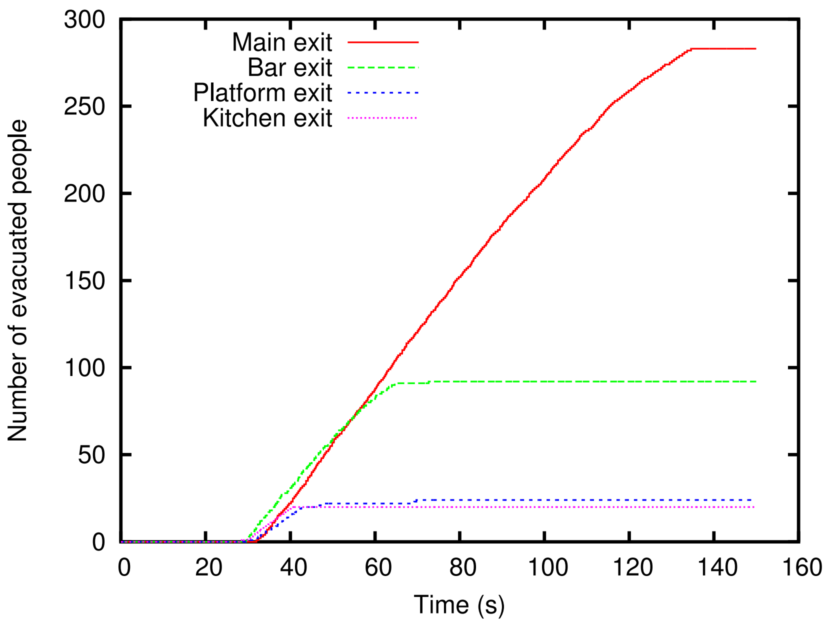
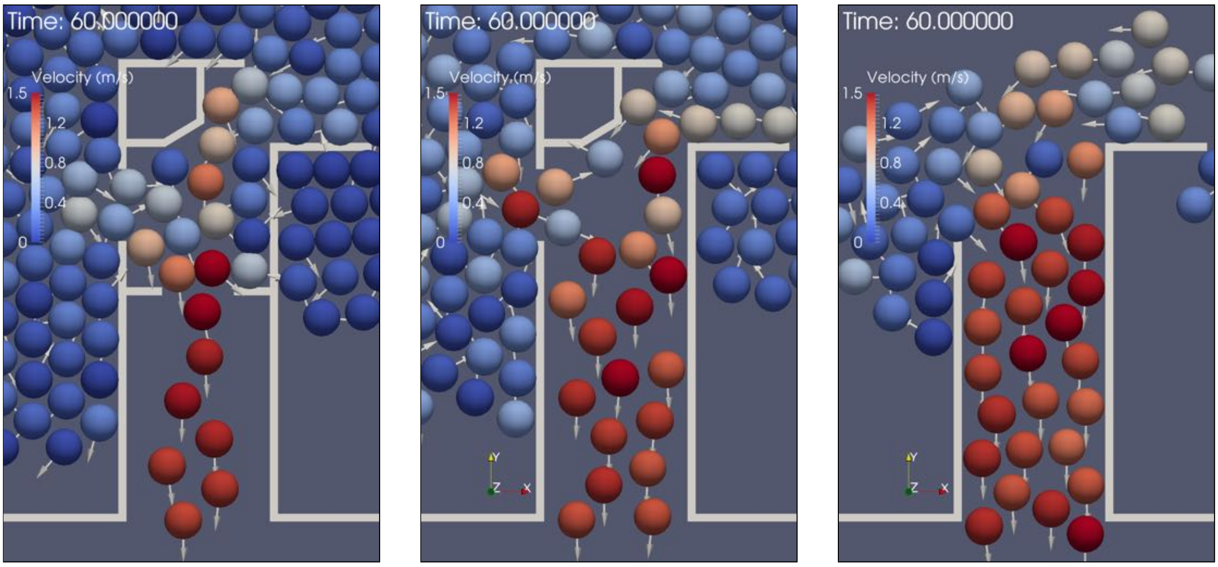


Figure 18: Evacuation curves of all four different exits in the nightclub.



(a) (b) (c)

Figure 19: Outflow of people through the main exit with different geometries: (a) unaltered from the original, (b) removed vestibule walls, (c) removed vestibule and further ticket-taker walls.

the vestibule walls, the agent queuing occurs in the ticket-taker desk area, where narrow passages and the collision of people coming from opposite directions slow down the total evacaution. After that part of the geometry is deleted, the congestion builds up in front of the vestibule corridor itself. Each subsequent change significantly increases the agent flow rate as illustrated in Figure 20. The total evacuation times were 134.62 s, 92.68 s, 72.12 s respectively. Hence, the simulations suggest that a simple removal of the vestibule walls would allow almost all the people to escape within the 90 s limit (eight people left in the building at $t = 90$ s). This produces an improvement of around 31.2% with respect to the original geometry. Although an idealised scenario was analysed, such layout changes would have most likely sped up the real fire evacuation and saved many lives. A more complex change to the geometry applied around the ticket-taker desk resulted in an evacuation time improvement of 46.2%. At this point, a large part of that time is due to the initial delayed reactions of agents (uniformly distributed between 24 s and 30 s) to the potential accident at time $t = 0$ s.

In terms of the building geometry, further improvements of the outflow of people were limited to increasing the width of the main exit corridor, which became the bottleneck after the removal of vestibule and ticket-taker desk and walls. Although, such simulations were not run because of the time constraints of the project, it is expected that at some given width, the total evacuation time would be restricted by the bar exit instead of the main one.

4.2.3 Preventing injuries and comments on model performance

An efficient evacuation is crucial to prevent injuries and save people's lives in the cases of nightclub fires like the one in Rhode Island in 2003. All the building exits, and especially the main exit which people are the most familiar with, should be capable of handling panicking crowds and providing a quick and smooth evacuation. It was shown that a removal of small vestibule doors would have resulted in a significant improvement in the

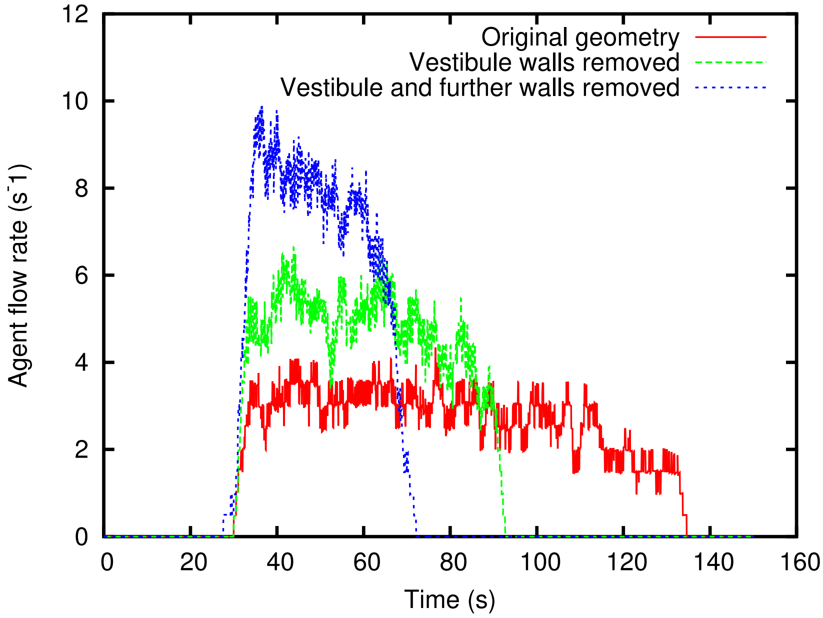


Figure 20: Measurements of agent flow rates through different configurations of the main exit.

evacuation time of The Station nightclub. In case of similar buildings with complex geometries, simple adjustments like widening the size of the door or relocating the ticket-taker desk could also prevent a number injuries or fatalities in a real evacuation emergency. The agentFOAM model provides a way of investigating such changes. The software allows for an identification of potential bottlenecks and congestion zones, and quantifying the improvements that modifications of the building geometry can bring.

Although the agentFOAM model demonstrated good predictive capabilities in The Station investigation, a number of improvements could still be made. The total evacuation times may vary significantly depending on what agent scheduling model is used. In reality, humans tend to adjust their preferred routes depending on the congestion they see or other information available (e.g. through signs or inside knowledge). In order to be able to analyse a truly ideal evacuation scenario, the agents should be able to figure out the quickest, and not only the shortest path to any of the exits. This could be achieved, for example, by incorporating the data on crowd densities in the agent scheduling algorithm.

Furthermore, it was observed that the agent-agent social repulsion force was active even between the agents located on two opposite sides of a border. Basing on empirical observations and experience, such approach is unrealistic and a fix should be applied.

Finally, the current way of implementing the social force model uses a lot of assumptions and many parameters which might vary significantly depending on the group being analysed. For example, it is debatable whether the radii and masses of the agents should be calibrated or taken as an intrinsic property of the analysed crowd based on people's average shoulder, hip or elbow-to-elbow widths. By rerunning the unaltered geometry nightclub simulation with the mean agent radius of 0.3 m instead of 0.24 m, the total evacuation time increased from 134.62 s to above 200 s, which shows how important the parameter is, despite being so arbitrarily defined in literature [19, 3].

5 Summary and Conclusions

Helbing's social force model for the motion of highly-stressed humans during evacuations has been understood and implemented in agentFOAM over the course of this project. A thorough verification and validation procedure was also employed to evaluate the model authenticity. During the verification process, the code demonstrated its capability of representing empirically observed phenomena like lane formation or arching. Highest quality data from a real emergency (classroom evacuation) and a controlled evacuation experiment (movie theatre) were also used to calibrate the key parameters of the numerical model to ensure its qualitative and quantitative results are as realistic as possible. Finally, simulations investigating the evacuation of The Station nightclub were run. The agentFOAM analysis of the unaltered building geometry correctly identified the main bottleneck to be around the vestibule area, which was responsible for congestion and decrease in the overall egress time. The model was then used to study the effect of two geometry modifications on people outflow from the nightclub. The results suggested that a removal of single lobby doors and nearby walls would have resulted in a 31.2% improvement in the total evacuation time. Almost all agents in the simulation managed to escape the building within 90 s, suggesting that many injuries and fatalities could have been avoided in the real accident in 2003 if such modifications were applied.

5.1 Suggested improvements and further work

The most important limitation of the model involved the process of setting the parameters. Agent radii, their desired speeds or other variables can have a significant effect on simulation results. Despite this fact, many parameters are still arbitrarily chosen basing on trial and error or depending on "what looks realistic". A more scientific procedure needs to be established and the calibration process ought to be standardised.

In terms of the equations implemented, a damping component could be added to reduce the "bounciness" effect observed between agents and borders in many simulations. Moreover, the code should be able to turn off the agent-agent interactions if a wall is located between them.

Finally, more advanced algorithms of agent scheduling could be implemented to represent a more realistic behaviour of evacuating humans. Agents should be capable of smarter decision making by, for example, analysing crowd densities and using this information to decide on the most efficient route.

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Appendix A Simulation Videos

A.1 Software verification

A.1.1 Lane formation

Description Formation of lanes by two groups of pedestrians walking in opposite directions. Periodic boundaries are used on left and right sides of the domain. Simulation was run with the final set of calibrated parameters. As their values are calibrated for more crowded and panic scenarios, agents in the lane formation simulation seem to "crash" into other pedestrians before changing their direction of motion.

Link https://youtu.be/yF7Cznx4wOI

A.1.2 Arching

Description An arch-like blocking of a narrow exit observed when people rush to escape. Simulation was run with the final set of calibrated parameters.

Link https://youtu.be/J25gvJD4ueo

A.1.3 Oscillations at bottlenecks

Description An empirical phenomena when two groups of people compete for a chance to move at a narrow bottleneck. Agent-wall repulsion force was turned off in the simulation (only reflection of agents present).

Link https://youtu.be/GFBBpGw8r3s

A.1.4 Path finding using the visibility graph

Description Verification of the visibility and shortest path (Dijkstra) algorithm with an agent trying to reach its final goal while avoiding the borders.

Link https://youtu.be/j2eqtGvMH_s

A.1.5 Agent-walls repulsion test

Description Simple test with three agents demonstrating the agent-walls repulsion force.

Link https://youtu.be/O8iLerABUPs

A.1.6 Fluctuation force test

Description A test to verify the fluctuation force implementation and find a suitable strength parameter. The animation presents the results with $\eta = 1000$.

Link https://youtu.be/BkvHnPJFXSE

A.2 Validation and real evacuations

A.2.1 Classroom evacuation

Description Simulations of the classroom evacuation with the final set of calibrated parameters. One animation uses a view from the top of the classroom and the other shows the results in a 3D perspective placed side by side with the real evacuation video.

Link 1 (2D) https://youtu.be/QNS3mFp9cn8

Link 2 (3D with real evacuation) https://youtu.be/Y_hmm9uhZ3s

A.2.2 Theatre evacuation

Description A 2D view of the final theatre evacuation simulation is shown. Queuing can be observed next to the front (top) exit.

Link https://youtu.be/Tns_BJG25nY

A.2.3 The Station nightclub evacuation

Description Simulations of the evacuation of The Station nightclub with unaltered and changed geometry. An initial uniformly distributed delay is applied to all agents (between 24 s and 30 s). The agents are coloured by their speeds and arrows are used to visualise their velocity vector direction.

Link 1 (original geometry) https://youtu.be/pw_l12lhWXw

Link 2 (vestibule walls removed) https://youtu.be/PzrnTmYXg5E

Link 3 (vestibule and further walls removed) https://youtu.be/NcM9C3_nhMI