Developing an Agent-Based Evacuation Simulation Model Based on the Study of Human Behaviour in Fire Investigation Reports

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Declaration

I, Tyng-Rong Roan confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

Abstract

Fire disasters happen every day all over the world. These hazardous events threaten people's lives and force an immediate movement of people wanting to escape from a dangerous area. Evacuation drills are held to encourage people to practise evacuation skills and to ensure they are familiar with the environment. However, these drills cannot accurately represent real emergency situations and, in some cases, people may be injured during practice. Therefore, modelling pedestrian motion and crowd dynamics in evacuation situations has important implications for human safety, building design, and evacuation processes.

This thesis focuses on indoor pedestrian evacuation in fire disasters. To understand how humans behave in emergency situations, and to simulate more realistic human behaviour, this thesis studies human behaviour from fire investigation reports, which provide a variety details about the building, fire circumstance, and human behaviour from professional fire investigation teams. A generic agent-based evacuation model is developed based on common human behaviour that indentified in the fire investigation reports studied. A number of human evacuation behaviours are selected and then used to design different types of agents, assigning with various characteristics. In addition, the interactions between various agents and an evacuation timeline are modelled to simulate human behaviour and evacuation phenomena during evacuation.

The application developed is validated using three specific real fire cases to evaluate how closely the simulation results reflected reality. The model provides information on the number of casualties, high-risk areas, egress selections, and evacuation time. In addition, changes to the building configuration, number of occupants, and location of fire origin are tested in order to predict potential risk areas, building capacity and evacuation time for different situations. Consequently, the application can be used to inform building designs, evacuation plans, and priority rescue processes.

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Table of Contents

List of Figures

List of Tables

1. Introduction and Background

Disasters happen every day all over the world, and these hazardous events, which threaten lives, force people to escape immediately from a dangerous area. To ensure people understand how to behave in an emergency when a hazard happens, evacuation drills take place to help people experience and learn evacuation skills. Although drills provide great opportunities for people to develop evacuation skills, they include two main drawbacks: they cannot realistically replicate real emergencies and people may suffer injury during the practice sessions.

Simulations of pedestrian evacuation processes have become a useful tool to overcome these issues. The models interpret human behaviour and emergency situations in a virtual environment, thus removing the risk to human safety that may be present during drills, as well as generating efficient evacuation routes for emergency plans. However, current models do not always accurately simulate pedestrian behaviour. This research seeks to develop an improved pedestrian evacuation model to ensure human safety in such events.

This introductory chapter describes the motivation for the research and relevant simulation background, followed by an outline of research issues, questions and methodology. Furthermore, main contributions are highlighted; an overview of the structure of this thesis is provided at the end.

1.1 Research Motivation

Disasters can be classified into natural disasters and man-made disasters. Wolshon *et al.* (2005) list a number of hazards that require evacuations and point out that some evacuations (particularly in the case of natural disasters) can only be carried out after the disasters occur. Natural disasters are a consequence of natural forces; they often have a significant impact in terms of financial and environmental damage, or lose of human lives. For example, floods, earthquakes, cyclones and tsunamis are amongst the worst natural disasters in history (Hough, 2008). Although natural disasters cannot be avoided, some can be predicted in advance, which can reduce the risk of hazards and enable evacuation warnings to be issued. Several techniques are used to make these predictions. Flood warning systems are utilised to predict flow rates and water levels according to flood forecasting, which is based on rainfall observation history, precipitation forecasts, stream flow data and river conditions (Beadle, 2008). An

Earthquake Early Warning system[1] in Japan warns the public or workers to protect themselves, shut down facilities, or shut off gas and electricity supplies in order to minimise damage (Web Japan, 2006; Nusca, 2011). Finally, cyclone forecasting uses meteorological data to predict a cyclone's future position, passage, and strength for the following few days (Roy Bhowmik and Kotal, 2010) and tsunami warning systems detect seismic waves[2] from nearby earthquakes and calculate the probable arrival times of tsunamis, thus permitting evacuation in advance (Lomax and Michelini, 2011).

On the other hand, man-made disasters are much more difficult to predict as they could happen anywhere at any time. As seen in the media, Figure 1-1 displays some examples of man-made disasters that involve evacuation processes. They include: (a) structural fires which occur in residential, industrial, commercial or office buildings and can easily cause death, serious injuries and damage (U.S. Fire Administration/National Fire Data Center, 2004); (b) terrorist attacks, such as the 9/11 World Trade Centre attacks and 7/7 London bombings, that threaten the safety of civilians due to terrorists' violence based on religious, political or ideological purposes; (c) gun shootings in which people use weapons for the purposes of bank robbery, revenge, or attack; (d) transport accidents, which occur on trains, ships and aircraft force people to complete an evacuation process when damage or structural failure is sustained; (e) bomb threats sometimes involve devices that create explosions and cause damage to property or harm people; (f) stampedes can happen when an environment is overcrowded, such as sport or music events, or during an emergency evacuation when people are pushing each other in order to escape from a hazard.

[1] The Earthquake Early Warning system provides advance notification of an earthquake when it is in progress. The timing of a warning depends on the conditions (such as distance from the epicentre) in which it can be issued and received.

[2] Seismic waves are elastic waves that propagate in solid or fluid materials. The waves of energy that travel through the earth are often caused by an earthquake, explosion, or similar energy source.

(Figure removed for copyright reasons)

Figure 1-1 Examples of man-made disasters which involve evacuation processes

Of the various types of man-made disasters, the Federal Emergency Management Agency (2010) claims that fire is the most common of all the hazards mentioned. Further evidence of this can be found in emergency response statistics from different countries shown in Table 1-1. According to the statistics, in 2010 the percentage of deaths and injuries that occurred in buildings exceeded 75%, representing a high number of casualties taking place in buildings rather than vehicles or the outdoor environment. Building evacuation plans are thus important because they help occupants to learn the safest and fastest egress route of a building before an emergency occurs (Ward, 2002). Therefore, this thesis focuses on disasters caused by building fires, as they often result in serious harm and damage; evacuation strategies should thus be carefully considered.

Table 1-1 Fire statistics from different countries in 2010 (China in 2009)

Country	Fire in Buildings/ Total Fire Incidents*	Deaths in Buildings/ Total Deaths	Injuries in Buildings/ Total Injuries
United States[(1)]	482,000/1,331,500 (36.20%)	2,730/3,120 (87.50%)	15,420/17,720 (87.02%)
United Kingdom[(2)]	93,700/286,500 (32.71%)	331/388 (85.30%)	8,900/11,100 (80.18%)
Japan[(3)]	27,137/46,620 (58.21%)	1,314/1,738 (75.60%)	6,386/7,305 (87.42%)
China[(4)] (Jan.–Aug. 2009)	45,786/89,664 (51.06%)	624/730 (85.48%)	306/398 (76.88%)
Nordic Countries[(5)] (Denmark, Norway, Sweden and Finland)	29,117/68,654 (42.41%)	312/349 (89.40%)	N/A

*Including fires in buildings, road vehicles, and the outdoor environment.
Source: [(1)]National Fire Protection Association (Karter Jr, 2011) [(2)]Communities and Local Government (Gamble *et al*., 2011) [(3)]Fire and Disaster Management Agency (Yabe and Esaki, 2011) [(4)]The Ministry of Public Security of the People's Republic of China (2009) [(5)]Nordstat.net (Centre for Resilience and Contingency Planning, 2011)

When fires are reported in the media, survivors are often been interviewed for the news. For example, the following statements show that people usually expect higher standards of safety with faster rescues, building configuration improvement and exit installation.

> *"Everyone was here. But it took too long for them to get in there and do something. It just seemed like it took too long. I think that's because it's just like a maze in there."* (Bignell and Richards, 2009)[3]
>
> *"There was only one exit, and people starting breaking down the doors to get out. Everything was in smoke. I couldn't see anything."* (Harding, 2009)[4]
>
> *"There was no time. Half the staff died because they were pushing people out the door."* (Hammerschlag, 2003)[5]

When an emergency occurs, the rate of egress can be significantly affected if an environment is unfamiliar to occupants, particularly in the case of public buildings (Ramachandran, 1990) such as underground/railway stations, stadiums, nightclubs, restaurants, hotels, and hospitals. These locations pose higher risks to the public during the evacuation process because the configuration and exit routes are not frequently used.

To ensure safety in public environments, pedestrian evacuation drills are regularly practised in offices, schools and residential buildings. These drills develop individual evacuation skills and familiarity with the environment, but in reality situations might differ in terms of different groups of people in different environments, especially in public buildings. Volunteers participate in emergency evacuation drills to demonstrate what happens when a disaster occurs in order to test the safety of public buildings. One report used questionnaires to study fire safety in underground rail transportation systems in different countries (Fridolf and Nilsson, 2012). The report summarised responses to evacuation drills and found that four out of seven countries use volunteers to run evacuation drills, but only one had passengers participate. Even this approach might not completely replicate a real life situation, because people could be less reactive than in an emergency due to announced drills. Another disadvantage of evacuation drills is the fact that people could be injured during the simulation. For example, 33

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[3] A blaze happened in a 12-storey tower flat in London, United Kingdom.
[4] A fire happened in the Lame Horse nightclub in Perm, Russia.
[5] A massive fire happened in the Station nightclub in Rhode Island, West Warwick, United States.

people were injured, one with a broken leg, during an Airbus evacuation drill, although the drill was considered successful in terms of people evacuating the plane in a short time (Rothman, 2006).

As a result, computer-based pedestrian simulations, a process of simulating how virtual agents behave in a scene using a computerised environment, have become a useful tool that could avoid injuries and reduce the budget for evacuation drills. In addition, they can help in understanding how humans behave in emergency situations, predict human behaviour and possible risks in such events, educate people to deal with hazardous situations, understand the reasons for serious casualties, and therefore avoid similar disasters. Moreover, the use of evacuation simulations to predict human behaviour during emergencies helps to identify any areas of risk and ensure that preventative measures (such as building redesign) take place prior to disastrous events.

The next section introduces previous research or approaches to both general simulation and the specific situation of emergency evacuation.

1.2 Simulation Types

Simulation is the operation of real-world facilities and processes (Law, 2007), which is also a particular type of modelling (Gilbert and Troitzsch, 2005; Maria, 1997). Seila (1995) identifies that simulation is an alternative realisation which approximates the system. The term "simulation" has been used for various applications in different fields and can be classified according to different purposes of simulation: realisation, prediction, and substitution (Gilbert and Troitzsch, 2005). One of the applications is pedestrian evacuation simulations, which are used to simulate human motion and crowd dynamics in emergency situations. The followings introduce a number of simulations in terms of three classifications that have been developed in different fields.

Realisation is the first purpose of simulation, which shows it can be used to promote a better understanding of facts or histories from the real world. For example, an electronic chip could simulate the metabolism of medicine in the human body (Odijk *et al.*, 2009). A special fluidic chip has the ability to screen new medicines rapidly, and was developed to understand how a medicine reacts in the body with different substances. Some studies have focused on climate models, which use quantitative methods to simulate the interactions between the atmosphere, oceans, land surface, temperature, ice sheets and the carbon cycle (Goosse *et al.*, 2008; Stott *et al.*, 2006; Church *et al.*, 2001).

Realisation of evacuation modelling simulates past scenarios or current facts in order to improve issues occurring in the environment. A scenario could be reconstructed to study the issues of exit design, building configuration or occupant load permission. In 2003, a blaze caused by pyrotechnic sparks occurred at a nightclub in West Warwick, Rhode Island, United States, killing 100 people and injuring another 230. The total number of people attending the event was estimated at 432, and this number far exceeded the maximum number (250) that should have been in the nightclub according to safety limitations (Hammerschlag, 2003). Researchers used a Dynamic Data Driven Shared Reality System (DDDAS), which is designed to study interaction between fire and agent models during a fire evacuation, to study the issues behind the Rhode Island nightclub fire. It was realised that a blockage around the main entrance was the significant factor in this horrible disaster (Chaturvedi *et al*., 2006).

Simulation could help managers and planners to understand the reasons for bottleneck areas in order to improve building configuration. For example, Covent Garden Underground Station is one of the busiest underground stations in London, United Kingdom; its original six gates often suffer congestion where passengers come out from the lifts to the exits. Therefore, a project improved pedestrian flow and congestion problems by changing gate lines by adding an additional five gates (LEGION, 2007). Furthermore, one of the annual events in London, the Notting Hill Carnival, has increasing problems with public safety due to the large number of people who join the parade along the street every year. A swarm model, which imitates a group of animals moving to the same target according to its attraction, was proposed to simulate the pedestrian flow of this area in order to control and manage crowds during the events (Batty *et al*., 2003).

Prediction is the second usage of simulation, which uses past experiences to predict future events. This type of model is not only used to study the impact of climate change (Maiorano *et al*., 2012), but is also helpful in the field of security and crime; for example, Johnson *et al.* (2012) studied the incidents of burglaries and developed an approach to predict future crimes in terms of data collected by the day of the week (daily burglary counts). For urban planners, Stevens *et al.* (2007) designed *iCity* as a novel tool for predictive modelling of urban growth, and incorporated it with a user friendly interface in the form of a Geographic Information System (GIS) to control modelling operations for urban land-use change. In the field of animal science, Roan (1991) focused on the prediction of pig growth and sow reproduction, and further introduced various models to predict growth, reproduction and feed intakes for different types of animals such as chickens, cows, and goats.

Evacuation models are used to simulate incidents that might occur in future events to avoid serious disasters. In 1987, a blaze suddenly started in King's Cross underground station in London caused by a discarded match on an escalator. The escalators were wooden and were still operating when the fire started, so the flames easily travelled upwards to the ticket hall. Within 15 minutes, the whole ticket hall filled with intense heat and thick black smoke, and a flashover caused serious damage. Therefore, Castle (2006) models pedestrian evacuation in King's Cross St Pancras underground station to help improve safety while this area is being developed as the largest integrated transport hub in Europe between 2000 and 2015.

In addition, prediction models are also commonly used for important events to ensure public safety. For example, the Olympic Games, which are held every four years and are major international events for summer and winter sports, have been studied to ensure the safety of thousands of athletes and onlookers who attend the event (Meland and Lintorp, 1994; Chown *et al*., 2006; Zhu *et al*., 2008). Johnson (2008) reviews different threats which have influenced previous Olympic Games and proposes a potential technique to address some of the issues by using interactive simulation software for the Olympic and Paralympic Games in London, 2012. Additionally, evacuation models can be used by designers and operators to ensure people are safe when evacuating from enclosed environments such as buildings and transport. Galea *et al*. evaluate occupant response under fire conditions in an earlier stage of ship design (2003) and explore the issues of the Blended Wing Body aircraft, which is one of the latest designs built to transport 1,000 passengers (2010).

Substitution is another purpose of simulation, using toolkits to represent real-life training. For example, flight simulators are a common training tool for pilots (Koekebakker *et al*., 2001) and, more recently, driving simulators help drivers to deal with potential challenges that might happen on the road and increase confidence in their driving skills (Parkinson, 2012). Therefore, learning simulations not only address hazard risks, but also reduce training time and cost. However, it is argued that computers are no substitute for real experience as they cannot simulate all problematic conditions in real situations, so it is suggested that people should not completely rely on the models (Duffy, 2007; Beadle, 2008; Hogan, 2008).

For the application of evacuation simulation, researchers use computer simulations to represent human and potential risks instead of running practical evacuation drills. For training purposes, people play their own roles through interface devices using the first person perspective to achieve various tasks (route navigation and correct response). A virtual evacuation training platform named “FreeWalk/Q” has been developed by Japanese scientists in order to understand social interaction during an emergency situation. Participants interact with other virtual agents in FreeWalk virtual space by taking various actions, such as walking, gesturing, speaking and hearing (Nakanishi *et al*., 2005; Murakami *et al*., 2005). Smith and Ericson (2009) believe fire safety is a difficult task for children, so they developed an immersive virtual reality interaction in a game-like learning environment to attract their interest. Children could learn knowledge of fire hazards, fire-safety skills and correct reactions from playing games. Furthermore, computer game technology can simplify the modelling of the virtual environment, easily display visual effects (fire and smoke) and use sound effects (fire alarms). Smith and Trenholme (2009) integrate commercial games with a real building environment, providing accurate floor plans and photo textures to create a realistic scenario for training fire evacuation procedure.

However, it was found that the results from game-based simulation were influenced by the participants’ experiences of playing video games, so dangerous behaviour, such as quickly opening a door through which the smoke came in, was discovered during the evacuation training (Smith and Trenholme, 2009). Consequently, evacuation simulation has become a tool to develop individual evacuation skills and understand potential human responses rather than high accuracy training. Mól *et al.* (2007) also emphasised that the aim of virtual simulations is to aid evacuation procedures rather than substituting actual human response, which supports the points made by people who feel that using computers cannot substitute for real life (Section 1.2).

Modelling Requirements

These three classifications of simulation have different levels of requirements regarding criteria such as realism, accuracy and processing speed. Firstly, realism is the representation of objects, phenomena, actions or scenes from the real world. Secondly, accuracy is the degree of match to the actual quantity. Thirdly, processing speed is the time that a model takes to calculate the whole process and finish its simulation.

The models for realisation purposes are to understand the facts from the real world, so realism is the most important. To predict the impacts of future events, both realism and accuracy are important. For the purposes of realisation and prediction, processing speed is considered an unimportant requirement. To ensure people can be effectively trained using simulation tools, the requirements of realism and accuracy are high and processing speed should be fast in order to give immediate reactions.

1.3 Research Objectives and Questions

This thesis aims to develop an evacuation model to understand an overall pattern of evacuation movement from the interactions of people, fire and space, so the model is developed as a third person perspective to simulate the evacuation procedure, which meets the classification of realisation and prediction. Therefore, the following chapters of this thesis focus on the review, development and discussion of realisation or prediction purpose types of models. Based on the literature review, a number of issues that influence the results of evacuation simulations are identified in Section 3.2. To conclude, the objectives of this thesis are developing a fire evacuation model that can be used for realisation or prediction purposes and addressing the selected issues (Section 3.3.1) to ensure the realism and accuracy of simulation results.

To achieve the objectives, two main research questions and sub-questions of this thesis are consequently outlined. The methods of addressing these questions are briefly introduced below and full details can be found in Section 3.4.

1) Can an evacuation model be developed based on the study of fire investigation reports?

- What information can be extracted from fire investigation reports to be built into evacuation models?
- What kind of evacuation behaviour can be identified from fire investigation reports?
- How can evacuation behaviour be encompassed in evacuation models?

To model realistic situations in an evacuation, human behaviour should be observed from real disasters. Therefore, a novel data collection method for studying human evacuation behaviour is proposed, using fire investigation reports (Chapter 4) to address the difficulties of data collection and analysis from existing fire events. Firstly, a number of fire investigation reports are collected from authorised investigation teams. Next, the contents of fire reports are examined to identify if they can be extracted and built into evacuation models. The qualitative analysis of human evacuation behaviour and evacuation phenomena is then developed to behavioural rules in the evacuation model.

2) Which combination of navigation algorithm and pedestrian size simulates results that are closest to real life situations?

- Which algorithms should be developed in the evacuation model?
- What issues do the current navigation algorithms encompass?
- How can the limitations of current navigation algorithms be improved?
- What size of pedestrians should be developed in the evacuation model?

After various behavioural rules are established in the model, the model requires a suitable navigation algorithm and pedestrian size in order to simulate the evacuation movement efficiently and accurately. In the literature, an issue that affects the results of pedestrian egress selection and total evacuation time exists (Section 2.6.4). As a result, the model uses the modification of navigation algorithms (Section 6.3) to simulate evacuation behaviour, movement and phenomena in the form of a model. To ensure the usage of the model, two navigation algorithms and two pedestrian sizes are tested in this research. Once the evacuation model is developed, different combinations of navigation algorithms and pedestrian sizes will be identified if suitable to realisation or prediction types of usages (Section 10.4).

1.4 Summary of Contributions

This thesis contributes to the development of the evacuation model by studying human behaviour from fire investigation reports, which efficiently build different evacuation scenarios based on information taken from a range of fire disasters. The following provides a summary of the six contributions and the full details are described in Section 11.2.

1) Studies human behaviour in an efficient way by analysing fire investigation reports

The method of studying human behaviour through the examination of fire investigation reports was selected because of issues with using video recordings and questionnaires (see Section 2.2.3). Using fire reports reduces the time that would be spent analysing video recordings in a specific fire case and increases accuracy by taking into account evidence other than that only observed by the occupants in the fire. In addition, this is a novel use of a different source of data, as no research has been conducted using this way of studying human behaviour before.

2) Additional evacuation behaviour - approaching windows

Many fire reports mentioned that occupants tried to jump from windows or were rescued by fire fighters via windows (see Section 4.3.2.2). Therefore, the model develops windows as an egress selection to simulate the situations that people in lower storeys could approach windows and escape from fire. This is not included in existing evacuation models.

3) Estimates the number of injuries

The model simulates both the numbers of deaths and injuries, which are not simulated in many evacuation models. The number of injuries is as important as the number of deaths; occupants who suffer injuries have a high possibility of dying at the scene.

4) Identifies risk level by areas

The model also classifies potential risk areas and calculates the number of deaths in each region, which has not previously been simulated in existing evacuation models. This prediction can suggest priority rescue plans to fire fighters for a faster rescue or help the owners to make improvements to avoid many deaths occurring in one place.

5) Improvement of navigation algorithms

The model improves the standard navigation algorithms that were selected for calculating pedestrian movement. After the improvement, potential movements between two points increased from a fixed path to multiple route selections.

6) Validating the evacuation model by the combinations of different navigation algorithms and pedestrian body sizes

This thesis uses a new validation method on simulation results by comparing different combinations of navigation algorithms and pedestrian body sizes. These comparisons provide an overall view of the influences that different navigation algorithms and pedestrian body sizes might cause in the model.

1.5 Thesis Structure

Chapter 1 has introduced the motivation for developing evacuation models, the background of general and evacuation simulations in terms of three categories (realisation, prediction, and substitution). Next, the aims and objective of this thesis are proposed. In addition, the overall of research questions and main contributions of this thesis were summarised, and this section introduces the structure of the thesis by outlining the contents of each chapter, as displayed in Table 1-2.

Table 1-2 Thesis structure and contents by chapter

Introduction and Background	Chapter 1			
	Motivation	Simulation Background	Research Overview	Thesis Structure
Contents of Evacuation Modelling	Chapter 2			
	Evacuation Behaviour and Phenomena	Modelling Approaches	Navigation Algorithms	
Developing Research Questions	Chapter 3			
	Issues Identification	Research Questions		
Developing an Evacuation Model	Chapter 4	Chapter 5	Chapter 6	
	Study Fire Investigation Reports	Model Design	Model Implementation	
Simulation Outcomes	Chapter 7	Chapter 8	Chapter 9	
	Preliminary Simulation Outcomes and Evaluation	Main Simulation Outcomes	Simulation Outcomes of Different Scenarios	
Discussion	Chapter 10			
	Review and Discussion of Simulation Results	Selecting the Optimal Approach	Research Differentiation	
Conclusion and Further Work	Chapter 11			
	Thesis Conclusion	Contributions	Further Work	

Chapters 2 comprise the literature review in relation to evacuation modelling, reviewing studies about human evacuation behaviour, modelling approaches and navigation algorithms. Firstly, methods of studying human behaviour are introduced and a number of human evacuation behaviour and phenomena are identified. Secondly, complexity and typical evacuation modelling approaches are introduced. Finally, different navigation algorithms are described and compared to each other.

Chapter 3 outlines the development of research questions. Firstly, a number of issues are identified and discussed from the previous research. Secondly, addressing issues are selected based on the consideration of potential solutions, modelling criteria, ability and time available for research. Therefore, research questions are established to address the selected research issues and achieve the objective of this thesis. Finally, three main criteria for evacuation modelling are defined in order to validate the results of the model.

Chapters 4 to 6 reveal the processes used to develop the evacuation model. To study human behaviour, a new method of analysing human behaviour in fire investigation reports is proposed. Chapter 4 introduces the background and contents of fire investigation reports, the collection of fire reports, and the human behaviour identified from the fire reports. Chapter 5 develops three types of agents and their interactions based on the selected human behaviour for simulating evacuation behaviour and phenomena in the model. In addition, sensitivity tests are checked before apply to actual fire disasters. Chapter 6 applies generic human evacuation model to modified navigation algorithms and selected fire disasters.

Chapters 7 to 9 display the simulation results of the model. Chapter 7 introduces the evaluation of the preliminary model to examine whether the scenarios, with designed agents and parameters, recreated the real life situations. To validate the model, five different tests are developed to examine the criteria of evacuation modelling, and the simulation results and the comparisons of results and fire statistics, if applicable, are displayed in Chapter 8. Chapter 9 presents the results of different grid size scenarios and proposes alternative scenarios, which modify parameters and configuration in one of the existing scenarios, to identify the influences of these changes.

Chapter 10 presents an overall comparison of the different scenarios in the model and a review of the developed evacuation model. In addition, impacts caused by modelling assumptions and parameter decisions are discussed, and an optimal approach for the model is decided based on the validation of simulation results. Finally, research differentiations are highlighted and compared to the previous work.

Finally, Chapter 11 draws conclusions from the research, identifies contributions made to the development of the evacuation model, and presents the limitations of this work and potential areas for further research.

2. Evacuation Behaviour and Modelling Approaches

Introduction and Background	Contents of Evacuation Modelling	Developing Research Questions	Developing an Evacuation Model	Simulation Outcomes	Discussion	Conclusion and Further Work
Ch. 1	Ch. 2	Ch. 3	Ch. 4, 5 and 6	Ch. 7, 8 and 9	Ch. 10	Ch. 11

2.1 Introduction

Evacuation simulation involves simulating crowd dynamics and pedestrian movements during emergency evacuations. An evacuation model is a simulation of people's navigation of escape routes, which are calculated by a navigation algorithm. Therefore, studies investigating human behaviour, types of modelling approach and calculations of navigation algorithms were reviewed in order to develop a suitable evacuation model. Figure 2-1 illustrates the elements involved in developing evacuation models, including study of evacuation behaviour, virtual occupants, modelling approaches and navigation algorithms.

This chapter explores the elements of people and evacuation behaviour that occurred in the existing models. To create evacuation phenomena in models, human evacuation behaviour are commonly studied by video recordings and questionnaires. Based on observation and experiments, individuals' characteristics are defined for virtual occupants in evacuation models. Following that, different types of modelling approaches and navigation algorithms are introduced and compared.

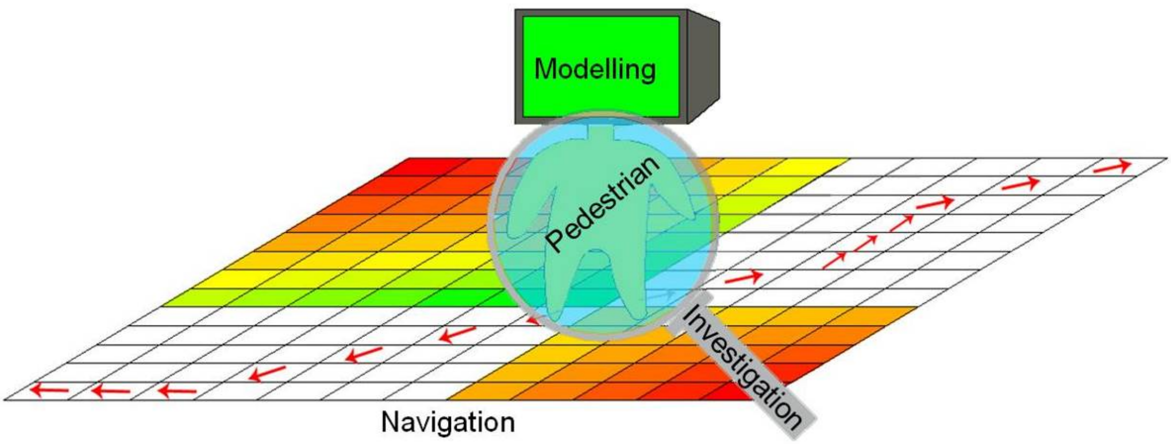

Figure 2-1 The elements involved in modelling an evacuation simulation

2.2 Study of Human Evacuation Behaviour

Evacuation behaviour can be observed in real life disasters scenes, evacuation drills or related experiments to understand how humans behave during evacuation. This section introduces two common methods that are used to study human behaviour: analysis of video recordings and questionnaires/interviews. Following that, a number of evacuation behaviour is identified from the past research.

2.2.1 Observations Methods

1) Video Recordings

Human behaviours and activities are easily captured by video recordings. The following information can be found through the observation of videotapes: the number, gender, age, location, mobility, role status (staff or customer), activities, and actions of each pedestrian at each time step. In addition, individual pre-evacuation times, evacuation times, and travel speed can be calculated according to an analysis of time steps. For example, the actual number of people who evacuated through each exit and individual evacuation times were recorded in videos taken of an announced evacuation drill of a retail store (Cheng *et al*., 2009).

Sandberg (1997) analysed individual characteristics, pedestrian evacuation movement, and travel speed from CCTV recordings of different unannounced evacuations in large retail stores, and Gwynne *et al*. (2003) collected pre-evacuation times and total evacuation times from hidden cameras, which recorded the movement of staff members and patients in a hospital. One of the common findings from both studies is that staff members play a different role to guests or patients, because the latter usually search for information and focus on evacuation, whereas employees instruct them on how to exit the building.

In addition to normal environmental conditions, smoke scenarios (Kobes *et al*., 2010a) and light-out conditions (Jeon *et al*., 2011), during which power was cut off for the duration of the evacuation, have been conducted to study navigation behaviour at different levels of visibility. Other studies have used video recordings to analyse group behaviour (Lee *et al*., 2007), travel velocities on stairwells (Fang *et al*., 2012) and the dynamic behaviour of walkers and crawlers (Nagai *et al*., 2006).

2) Questionnaires and Interviews

This method usually accompanies video recordings in order to provide additional information about human characteristics and other behaviours that cannot be analysed from the video recordings during evacuation. In addition to the video recordings of Sandberg's study (1997), questionnaires completed by customers of the retail stores were analysed to understand occupants' profiles and their responses. A number of personal characteristics such as age, gender, social affiliation, familiarity with the building, occupancy density by area, communications, activities prior to alarm and exit choices were analysed from the collected questionnaires. In some cases, video recordings were not available or lacked information, so human behaviour could only be assessed through questionnaires. For example, a post-fire survey was carried out after a fire in a multi-storey office building, and a number of factors that influenced human behaviour were examined (Zhao *et al.*, 2009).

These questionnaires usually include questions targeting personal profiles, familiarity with the environment, evacuation response, egress selection and other information in relation to the evacuation process. Analysis of all the questionnaires could provide information to help understand human behaviour during an evacuation; for example:

- **Gender** determines whether males and females behave differently during the evacuation. For example, women have a shorter pre-evacuation time than men (Zhao *et al.*, 2009) and they also behave differently in finding the origin of the fire, helping others to evacuate, evacuating from the building and calling the fire brigade (L. Shi *et al*., 2009).

- **Age** of people influences individual physical, psychological and social behaviour, which has an impact on pedestrian evacuations. The elderly have longer reaction times or are slower to travel than normal adults during an evacuation (Legg and Adelman, 2009; Koo *et al*., 2012).

- **Familiarity with environment** shows how occupants navigate an egress route during evacuation and the efficiency with which emergency exits are used within an environment. In some cases, people select familiar exit routes instead of an emergency door, since they have no idea where it will lead (Sime, 1995; Proulx *et al*., 1996; Winerman, 2004).

- **Pre-evacuation activities** influence individual pre-evacuation times and evacuation responses before the decision to evacuate is made. A number of activities such as snoozing, watching TV and working have been examined to understand the influences of these pre-fire activities on subsequent actions and pre-evacuation times (Zhao *et al*., 2009).

- **Group behaviour** examines whether people who accompany others behave differently to individuals. For example, occupants' response times, travel speeds, and navigation behaviours change when they observe the behaviour of group members (Galea and Blake, 2004), and delays are often caused by people gathering family and friends before starting to evacuate (Proulx *et al*., 1996).

- **Route selection** helps understand how people select a route and exit to escape. In Sanberg's research (1997), the number of people who evacuated through each exit was evidenced in video recordings and their reasons for selecting this exit were explained in questionnaires.

2.2.2 Observation Results from Video and Questionnaire Analysis

Human evacuation behaviour is defined as actions that occupants take in the pre-movement stage and evacuation stage. Based on the observations from the previous studies, a number of evacuation behaviour is identified below and they are categorised as different stages in a pedestrian evacuation timeline (Figure 2-2). An overall evacuation timeline begins from the moment a fire alarm is sounded to the point at which the evacuation ends. The period between people hearing the fire alarm and the person to begin evacuating is called the pre-movement stage, and evacuation stage starts from individuals start evacuating to the time that people successfully escape the building.

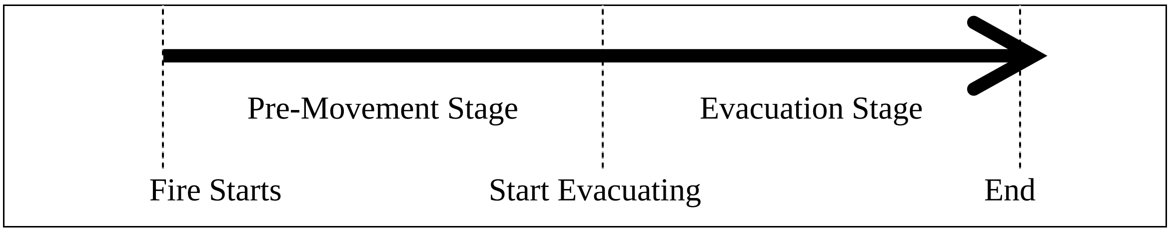

Figure 2-2 Pedestrian evacuation timeline (adapted from CFPA Europe, 2009)

Pre-movement Stage

The following list displays various pre-movement activities that have been analysed from a retail store (Sandberg, 1997), an office building (Zhao *et al*., 2009), a hospital (Gwynne *et al*., 2003) and others (Kobes *et al*., 2008).

- Investigating the incident
- Discussing with other people
- Helping or alerting others
- Fighting the fire
- Calling the fire brigade
- Saving material property
- Ignoring the alarm
- Performing a computer shutdown
- Collecting items
- Sleeping
- Determining an escape route

Evacuation Stage

The following list displays human behaviours during evacuation that are summarised from a number of studies (Sandberg, 1997; Kobes *et al*., 2008; Galea and Blake, 2004).

- Evacuating to the nearest exit
- Evacuating to the main entrance
- Evacuating to the door through which they entered
- Standing by or jumping out of windows
- Breaking windows for fresh air
- Passing through smoke
- Fire fighters moving in opposite directions
- Changing egress routes
- Seeking refuge
- Feelings of fatigue
- Using lifts
- Moving in an orderly way
- Groups evacuating together

2.2.3 Issues of Using Video Recordings and Questionnaires

Every disaster is unique as it is influenced by a complex web of factors such as human behaviour, building configurations, materials, fire types, the spread of smoke, airflow, temperature and many other elements. Any of these factors could lead to a significant building disaster. To build an evacuation scenario of a real-life disaster, buildings are based on existing floor plans and human evacuation behaviour is simulated according to witness statements or video recordings. Although video recordings provide primary sources to understand what people behave at each time step of the video, some limitations lead a simulation development inaccurate, costly and inefficient. In addition, many evacuation models were built based on the study from evacuation drills, and they can thus only hope to simulate a similar event. Therefore, it is important to understand how people behave in real life disasters.

Since this research focuses on fire disasters, it is difficult to use video recordings to gather all the information together from the damage fire scenes. Firstly, it is difficult to collect a large amount of primary video data after fire disasters. Data might be destroyed by fire, and sometimes video cameras do not cover all the space. Secondly, it is difficult to identify human behaviour in a scene that is filled with fire/smoke, and it might take a long time to analyse one case.

The accuracy of a questionnaire or interview is considered relatively low, because people's actions sometimes do not reflect their answers (Simkins, 2005). For example, one occupant said he used a lift to evacuate during an office evacuation drill, but there was no evidence of any of the occupants trying to take the lift in the video recordings (Proulx *et al*., 1996). In addition, witness statement can only be taken from those who survive a disaster, and the reasons why victims stayed in a room or selected an egress route are impossible to confirm after they have perished at the scene, so their response and what happened during their evacuation cannot be ascertained.

2.3 Review of Evacuation Behaviour and Phenomena in Evacuation Models

Section 2.2.2 displays a list of evacuation behaviour analysed from video recordings and questionnaires. Most of the evacuation simulations were developed to simulate a main goal, which is escaping from hazards and evacuating the building in a safe period of time. This section reviews a number of behaviours and evacuation phenomena that have been simulated in current evacuation models, such as navigation behaviour and evacuation phenomena that might occur near an exit.

2.3.1 Navigation Behaviour

Moving Towards a Destination Individuals plan their movement from their current location to the selected destination in advance or in real time. During the movement, people tend to select a path that minimises both angular and distant displacement for the next few steps (Antonini, 2005). Figure 2-3 displays the process of a person moving to an exit in a spatial location, and a path is selected in terms of the minimum angle and distance at each transition point. The parameter d_c is defined as an individual current direction, and d_d is the direction of the destination. To change the direction of movement from d_c to d_d, d_{cd} is the pedestrian's desired direction and θ_{cd} represents an angle from the current direction to the destination.

(Figure removed for copyright reasons)

Figure 2-3 The elements of behaviours demonstrating movements towards a destination (adapted from Antonini, 2005)

Avoidance This behaviour captures the phenomenon of people changing their direction of movement in order to avoid collisions with other pedestrians or obstacles. Foudil (2009) classified collision into three types: towards, away and glancing, as presented in Figure 2-4. Firstly, a towards collision is face-to-face interaction when two individuals are walking towards each other, and they change their direction of movement, walking speed, or both. Secondly, an away collision happens when a person walks at a high speed behind another person, and the person decreases his/her walking speed to follow another person or walks faster to pass people. Thirdly, a glancing collision is a side-on collision between two individuals who are moving from different directions and might crash at a specific location. In this type of collision, people would only slightly change their walking directions and speeds in advance.

(Figure removed for copyright reasons)

Figure 2-4 Three types of collision: toward collision, away collision, and glancing collision (adapted from Foudil, 2009)

Herding This behaviour comprises a group of occupants moving from one place to another place by following each other; it usually happens when people are highly uncertain about their decision-making. The principle of Social Proof, which is a psychological phenomenon that occurs in ambiguous social situations when people are unable to determine the appropriate mode of behaviour, shows that people usually consider a decision correct because many people are doing the same thing (Cialdini, 2009). For example, people tend to follow crowds when they are evacuating from a building. This situation might cause a serious bottleneck around an exit and slow the evacuation process.

Follow-the-Leader Some pedestrians are influenced by leaders who attract them, and they follow the decision and movement of those leaders. Figure 2-5 shows leader following behaviour with a combination of various behaviours from different studies (Antonini, 2005; Xue, 2006; Robin *et al.*, 2009). For example, separation behaviour (avoidance of collision between occupants), arrival behaviour (followers stay around the leader at a slight distance) and move away behaviour (followers avoid moving into the leader's near future path). In addition, the leader remains within a certain range of distance and walking velocity from the potential followers.

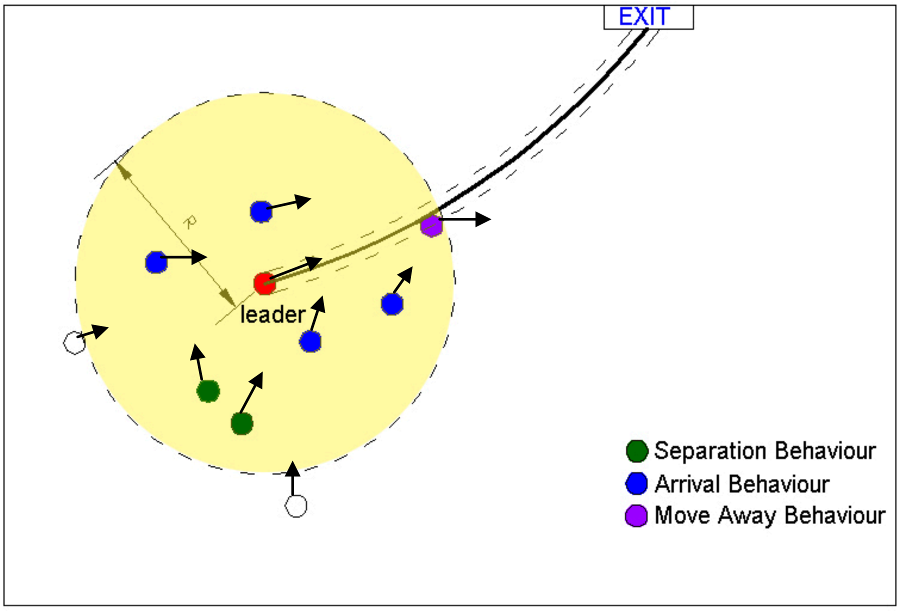

Figure 2-5 The conditions of leader and potential leaders behaviour

2.3.2 Emergent Evacuation Phenomena

Arcing and Clogging This phenomenon happens when an exit is overloaded by a large group of people who are moving towards the exit at the same time. Figure 2-6 shows an arcing phenomenon around an exit due to a bottleneck of pedestrian flow. The arcing phenomenon became more evident when pedestrians' desired velocity increases (Song *et al*., 2006). This conclusion was based on experiments with different pedestrian velocities. In their tests, pedestrian movement was regular, coordinated and continuous when the desired velocity was slow or normal (below 1.5 m/s). In contrast, pedestrian movement became irregular, discontinuous and achieved an avalanche-like distribution because of friction and repulsion became stronger when the desired velocity increased.

(Figure removed for copyright reasons)

Figure 2-6 Arcing shape of pedestrian flow around an exit (adapted from Helbing *et al*., 2000)

Queuing People start queuing when a number of people are moving towards the same destination or following the same process, as displayed in Figure 2-7. Okazaki and Matsushita (1993) introduced three types of human queuing behaviour: the first type is the movement in front of counters when people arrive at a queue, wait in the queue, move forward, are served and depart from the counter. Type 2 is the movement in front of gates when people arrive at a gate, are served and pass through the gate. The last type is the movement of getting on and off, whereby people wait for a vehicle to arrive, wait for the door to open, and climb aboard after passengers leave. Of the three types of queuing behaviour, type 2 often occurs in evacuations when people are queuing in front of an exit to evacuate the building.

(Figure removed for copyright reasons)	**Type 1** Location: Bank, Ticket Box, Shop Counter Step1: Arrive Step2: Queue and move forward Step3: Be served Step4: Departure
(Figure removed for copyright reasons)	**Type 2** Location: Station Gate, Security Check Step1: Arrive Step2: Be served Step3: Pass through
(Figure removed for copyright reasons)	**Type3** Location: Platform, Bus Stop, Lift Step1: Vehicle arrives Step2: Doors open Step3: Passengers leave Step4: On board

Figure 2-7 Human queuing behaviours: movement at the counters, movement passing through gates and movement when boarding vehicles (adapted from Okazaki and Matsushita, 1993)

Faster is Slower The arcing and clogging phenomena influence the development of a bottleneck, which the capacity of the exit decreases when people move faster (Cepolina, 2004; Helbing *et al*., 2002). Figure 2-8 displays the faster-is-slower phenomenon using desire for velocity versus evacuation time in social force models (Section 2.5.2) and CAFE models (Section 2.5.4). The figure shows pedestrians spent longer evacuating when their desired walking pace exceeded a certain speed, and the reasons individuals decreased their speed were the effects of clogging, arcing and strong inter-personal friction during evacuation (Song *et al.*, 2006).

(Figure removed for copyright reasons)

Figure 2-8 Faster-is-slower phenomenon in a social force model and a CAFE model (Song *et al*., 2006)

2.4 Human Navigation Characteristics

Even though all the individuals have the same navigation behaviours, evacuation phenomena occur differently in every disaster. This is caused by a variety of characteristics that makes each individual unique, as individual different decision time would make a continuous impact on the evacuation process. However, it is beyond the scope of this thesis to discuss all of the factors that influence human evacuation behaviour. This section introduces three main basic characteristics that influence pedestrian navigation in evacuation models.

Body Size Body dimensions influence a pedestrian's occupied space and population density in an environment. Lackore (2007), from the Chassis Technical Committee of the Fire Apparatus Manufacturer's Association presents human body size by using anthropological classification and comparison with fire fighters. The size of a human torso is defined as body width, which is measured from shoulder to shoulder, and body depth, which is measured, by chest depth as displayed in Figure 2-9. According to the statistics of this report, the average body size is 20.6 inches (52.3 cm) by 12.3 inches (31.2 cm). Although this report limited participants to fire fighters who wore bunker gear, the model of this thesis designs body size with 0.5 m^2 or 0.3 m^2 for representation of a normal, fully clothed adult (Section 6.2).

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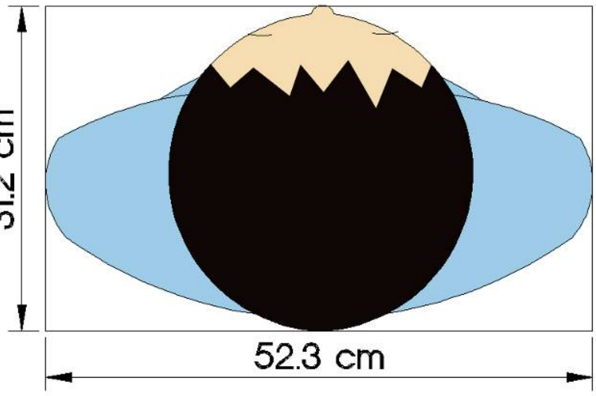


Figure 2-9 Representation of human body size in a grid

Visual Field The definition of an average human monocular visual field is from 60º up to 75º down and 100º temporal to 60º nasal from fixation (Spector, 1990); Figure 2-10 illustrates the range of the human visual field. In other words, an individual's field of vision extends approximately 135 degrees vertically and 200 degrees horizontally (Rauscher *et al.*, 2007). One of the human walking behaviours observed is people tending to use the centre of their visual range when moving from their current position to the next step, so pedestrians usually maintain their course within a minimum displacement of the angle to avoid frequent variation of direction during their movement (Robin *et al.*, 2009). In real fire disasters, some people turn around and check what has happened behind them because of an unusual sound or smell, according to interviews on the local news (Chan, 2008; Blake, 2012), so they are not only aware of situations that happen in front of them.

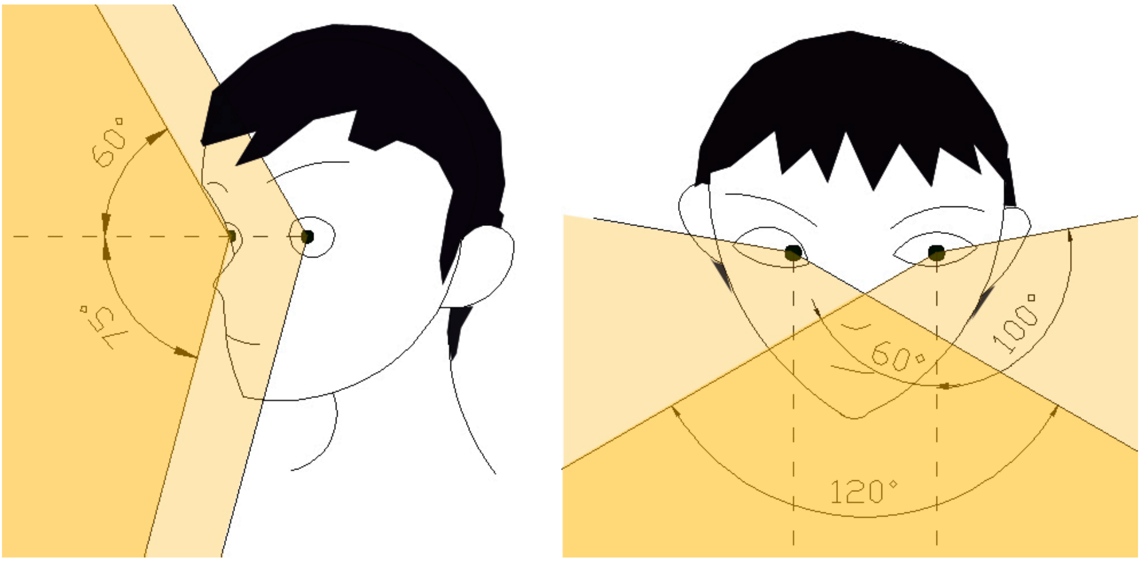


Figure 2-10 General human vertical and horizontal visual field

Walking Speed The speed of an individual pedestrian is an important variable for modelling pedestrian movement and is affected by different ages and genders. According to the statistics in the database of an emergency evacuation model (L. Shi *et al*., 2009), the walking speeds of children and the elderly are generally slower than that of average adults, and people move much more slowly on staircases than on a flat plain (Table 2-1). The same phenomena often occurs when people are escaping from a large scale or a high-rise building, and they sometimes stop to recover their energy after walking for a long time (Pelechano and Malkawi, 2008).

The definition of the age groups used in Table 2-1 is presented as follows: children are less than 14 years old, adults are between 14 and 65 years old, and people aged over 65 are defined as elderly (Yeo and He, 2009).

Table 2-1 Pedestrian average walking speeds in terms of different age and gender groups

Age and gender group / Average speed (m/s)	Children	Female Elderly	Male Elderly	Elderly	Female Adult	Male Adult	Adult
Walkways	1.08	1.04	1.05	1.04	1.24	1.30	1.27
Upstairs	0.29	0.27	0.29	0.28	0.30	0.32	0.31
Downstairs	0.31	0.26	0.29	0.28	0.36	0.42	0.38

2.5 Complexity and Modelling

The world is a mixture of simple and complex phenomena. Simple phenomena can generally be explained by simple mechanisms found in theories of physics, but the complexity of real world is difficult to be presented by any finite number of formal systems (Mikulecky, 2001). However, the term "complexity" has been argued and defined with different meanings as the following examples. Complex systems are built using simple rules to generalise from the complexity of the real world, containing many interactions between a large number of parts (Simon, 1996) and the science of learning systems (Davis and Simmt, 2003). The interactivity is mostly nonlinear and contains manifest feedback loops (Richardson *et al.*, 2001). Phelan (2001) considers that complex effects are influenced by simple causes and generative rules, but Gilbert (2004) considers complex systems should be determined as a whole system without partitioning it into parts or understanding the behaviour separately.

One of the common examples in complex systems is a school of fish as they perform interesting patterns of swimming behaviour. Individual fish's swimming direction is influenced by other's movements of its neighbours, and a fish school automatically organise themselves as a group without a leader (Huth and Wissel, 1992). Evacuation processes are another example of complex activities, because every disaster is unique and difficult to predict. In a real fire evacuation, personal behaviour is unique and pedestrian movement is influenced by the individual, other people, obstacles and any situation (such as fire/smoke spread or building collapse) in an environment. The observations of such systems can be classified into three key features, including locally controlled, the emergence of bottom-up and collective learning systems. The following examples use pedestrian flow (Figure 2-11) to explain the phenomena of each feature.

(Figure removed for copyright reasons)

Figure 2-11 The self-organisation of bi-directional pedestrian flow (adapted from Zhang *et al.*, 2011)

Locally Controlled Individual entities behave in terms of their own characteristics and motivations, but their behaviour is influenced by others around them. For example, an individual (green dot no. 1) who tries to pass through the crowds seeks available space by following the person in front of him (Figure 2-11). The interactions between entities are based on localised rules and information.

The Emergence of Bottom-Up Action The phenomena of self-organisation (Ashby, 1947) show the interactions among random states of entities at a local level evolve toward a pattern at the global level. Followed by the example, a self-organised lane is formed in the crowd when every individual follows other's movement. Figure 2-11 shows four separate lanes while two groups of pedestrians moving in opposite directions.

Collective Learning Systems Entities learn and dedicate to collective knowledge through interactions. Individuals do not observe any emerging phenomenon, but local interactions generate functional organisations at the global scale. When an individual (green dot no. 2) arrives, he learns the situations by interacting with the people in both directions and subsequently joins the formed lane in the crowd by walking behind another person (Figure 2-11).

In addition to fish schools and evacuation processes, complex systems have been widely used in different applications, such as ecosystems, stock market, climate systems, immune systems and social systems. More applications can be found in the fields of astrophysics, geology, medicine, economics, biology and technology. However, modelling and analysis of these complex systems is a difficult task because of nonlinear dynamics and unpredictable results. Hayek (1964) claims that the prediction of complex systems can only display a pattern of phenomena. Therefore, validating the model after development is challenging.

The discussion above provided an introduction of complex systems, and the following introduces the main application, evacuation models that are developed for the purposes of this thesis. Pedestrian crowd and evacuation movements have been studied in many years, and various types of evacuation models have been reviewed (Santos and Aguirre, 2004; Zheng *et al.*, 2009). To simulate the impact of evacuation that caused by individual behaviour, microscopic models are used to achieve the purpose. Therefore, three most typical modelling types that simulate these factors are introduced in more details as below.

2.5.1 Cellular Automata Models

A cellular automata model is a discrete space and time system, which divides space into regular grid cells and uses a state of local rules on each grid cell to change state. In addition, the calculation of CA models is made in discrete time steps, and the value of each cell is updated based on the adjacent values at the previous time step (Wolfram, 1983). In the 1960s, the first system of cellular automata (CA) was established by John von Neumann (1966). Generally, the rules of CA models are assigned to a 'true' or 'false' state using if-then functions. For example, a state of "*IF next-cell is the nearest to the exit=True THEN (IF next-cell is empty=True THEN walk)*" on a cell of an evacuation model would lead a person moving onto the next cell, which is closer to an exit, if the cell is not occupied by another pedestrian.

One of the famous cellular automata models is the Game of Life, which is a two-state ('alive' or 'dead') cellular automaton invented by John Horton Conway, a British mathematician; the game became well known after Martin Gardner published it at the Mathematical Games column of Scientific American (Gardner, 1970). The Game of Life was originally created by using a game board instead of a computer, in which the state of each cell is based on the sum of its surrounding values at the previous step rather than on their separate values. Figure 2-12 shows an example of the evolution pattern using the rules in the Game of Life. Every cell checks with its eight neighbours, horizontal, vertical, and diagonal cells, and the state of each cell changes according to the rules that are described below.

(1) Alive: A living cell remains alive when the cell has two or three living neighbours.

(2) Dead: A living cell dies if it has other numbers (not two or three) of living neighbours.

(3) Alive: A dead cell will come alive when it has exactly three living neighbours.

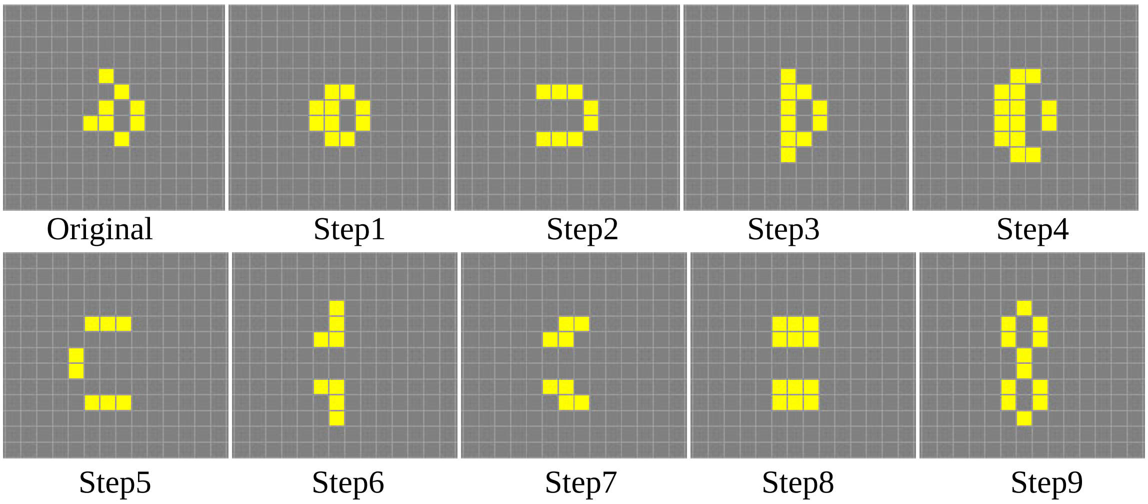


Figure 2-12 Cell pattern based on the rules of the Game of Life

In recent years, cellular automaton models have been widely studied in various applications with regard to pedestrian simulation. For example, Weng *et al.* (2006) presented various phases of pedestrian patterns in terms of walking velocities, and Yue *et al*. (2010) highlighted the relationships of velocity-density and flow-density in the study of bi-directional pedestrian flow. Other research focuses on the interactions between pedestrian and environment, such as pedestrian flow in one and two-exit rooms (Kirchner and Schadschneider, 2002), the influences of different exit widths and door separations (Zhao *et al*., 2006), and the impact of pedestrian movement caused by a state with/without obstacles in a single exit room (Varas *et al*., 2007).

2.5.2 Social Force Models

Helbing and Molnár (1995) have established a social force model, combining the idea of the gas-kinetic theory and social fields (Lewin, 1951) to simulate behavioural changes. Social force models simulate pedestrian motion by the following main forces (Figure 2-13): (1) Pedestrian desire: people normally walk at a desired velocity toward their destinations. (2) Interaction between occupants: people keep a certain distance from other pedestrians in terms of population density and desired individual walking speed. (3) Interaction with boundaries: people keep a certain distance from borders such as walls and obstacles. (4) Attraction: people are sometimes attracted by other pedestrians or objects; for example, family often stay closer to each other and people move toward doors instead of walls. These factors can be classified into two types of forces; the first is the *driving forces* that reflect the motivation of pedestrians who are moving towards a target at their desired velocities. The second is the *interaction forces* that form the interactions between pedestrians and objects, including socio-psychological and physical interactions. Finally, the total influence of a pedestrian is the sum of different forces comprising an occupant's desired speed and direction, pedestrian and border repulsion and attraction effectiveness.

(Figure removed for copyright reasons)

Figure 2-13 Forces from different interactions (adapted from Laufer, 2009)

Ever since the first social force model was introduced (Helbing and Molnár, 1995), it has been used and further developed to study pedestrian movement. In the following years, social force models were used to simulate human behaviour in normal, crowd and emergency situations (Helbing *et al*., 2000; Helbing *et al*., 2002). Other applications of social force models have also been implemented; for example, Parisi and Dorso (2005) revealed the influence of pedestrians' desired velocities and door widths in a single exit room, and Mehran *et al.* (2009) used a computer vision method to detect and localise abnormal human crowd behaviour in video recordings.

In addition, social force models have been modified by other approaches. The Helbing-Molnár-Farkas-Vicsek model (Helbing *et al*., 2002) was extended to study more realistic panic and non-panic crowd behaviour (Kaup *et al*., 2006), and an implementation of the social force model using the Verlet Link Cell algorithm[6] showed the efficiency of computation time compared to the results of Helbing and Molnár's study (Apel, 2004). Furthermore, human anisotropic characteristics and avoidance of

[6] The Vertlet link cell algorithm is a combination of the Verl*et al*gorithm and link cell algorithm, which is known from physical molecular dynamics computer simulations, using rapid calculation of the neighbour tables. The Verl*et al*gorithm calculates individual social force using an n^2-complexity within its radius range over a period. In order to reduce the complexity of social force calculation, the Verl*et al*gorithm is extended with the link cell algorithm, which divides the social force range into regular cells.

overcrowded areas have been considered in a social force model to improve existing problems with pedestrian movement (Hu *et al*., 2009).

2.5.3 Agent-Based Models

Agent-based models (ABM) are computational models for simulating social interaction with virtual agents. Four typical characteristics are classified based on the previous studies (Wooldridge and Jennings, 1995; Macy and Willer, 2002; Padgham and Winikoff, 2004): (1) Autonomous: agents take independent actions without being directly controlled by users or other agents. (2) Social: agents interact with other agents. (3) Reactive: agents adapt according to interactions and could respond to the environment. (4) Goal-directed: agents move directly towards a final target. The above characteristics imbue each agent with unique behaviours in order to grant autonomous decision-making and interaction with other agents.

A comprehensive overview of behavioural frameworks that are incorporated into agent-based models is described by Kennedy (2012) and Malleson *et al.* (2012). Two common behaviour frameworks are introduced here. Firstly, Belief-Desire-Intention (BDI) approach uses *belief* to represent agents' knowledge of the world, *desire* sets agents' goals and achievements, and *intention* defines the priority of achievements in their plans (Bratman *et al*., 1988). This approach is used for facility management (Dibley *et al*., 2011) and simulations of crowd evacuation (Lee and Son, 2008) and driver route choice behaviour (Dia, 2002). Secondly, PECS reference model simulates Physical, Emotional, Cognitive, and Social aspects of human behaviour. Schmidt (2005) uses brief examples to explain the factors and interactions as follows: agents look for food to maintain energy (physical conditions), emotions such as fear change by a state transition (emotional state), agents try to achieve their goals according to their willpowers (cognitive capabilities), and agents interact to each other (social status).

Crooks and Heppenstall (2012) claim three advantages of agent-based approaches when compared to other modelling approaches, including the capture of emergent phenomena, the study of systems in a natural environment and flexibility. Therefore, agent-based models have been widely used to study pedestrian movement since the simulation of bird flocking (Reynolds, 1987), which was one of the earliest agent-based models in terms of movement in social behaviour. Various aspects of human behaviour have been studied, such as group inter-relationships (Musse and Thalmann, 1997), steering behaviour (Reynolds, 1999) and individuals with disabilities (Christensen and Sasaki, 2008). One of the research teams in the UK proposed the STREETS model to investigate whether pedestrians' movements were influenced by spatial configuration and the distribution of attractions (Schelhorn *et al*., 1999), and another research team developed the PEDFLOW model to simulate pedestrian movement in a congested urban environment (Willis *et al*., 2000).

Moreover, pedestrian movement in agent-based models has been incorporated with fire scenes and building geometry in order to understand the interactions between human, fire, and geometry (Tang and Ren, 2008). Lin *et al.* (2008) applied multi-agent navigation graphs, roadmaps and navigation methods to simulate complex crowd behaviour in computer games. Additionally, agent-based models have been used to determine customers' store choice processes in terms of travel motivation, destination selection and approach to route choice (Dijkstra *et al*., 2009).

2.5.4 Combination of Different Approaches

Cellular Automata, Social Force, and Agent-Based are three common types of models that are widely used for evacuation simulation. As a result, various combinations of these models have been trialled to integrate the advantages of each modelling approach. This section introduces the modification in different studies.

<u>1) Cellular Automata with Social Force Approach</u>

The cellular automata approach has been combined with an aggregate representation of an environment. For example, a hybrid model has been developed by combining the advantages of fast computation and realistic movement from both approaches (Gloor *et al*., 2004). Moreover, Yang *et al.* (2005) proposed a discrete social force model, which is based on the methods of cellular automata models and social force models to simulate the phenomenon of kin behaviour. In addition, Song *et al.* (2006) proposed the Cellular Automata Force Essentials (CAFE) model, based on the traditional CA model, and the interactions between pedestrians are classified into three types of forces: attraction, repulsion and friction. This model was developed to simulate emergent evacuation in a single-exit room and then the results were compared with social force models.

<u>2) Agent-Based Cellular Automata Approach</u>

Agent-based cellular automata modelling has been used to simulate various pedestrian behaviours. Dijkstra *et al.* (2001) combined a multi-agent model with a CA approach to simulate pedestrian dynamic movement and gain insight into pedestrian activity behaviour in a shopping mall. Another pedestrian dynamic model used agent-based cellular automata approaches to simulate bi-directional pedestrian movement (Ronald and Kirley, 2006). Furthermore, Bandini *et al.* (2006) presented the Situated Cellular Agent (SCA) model to study crowd behaviour in an underground station with a platform and a train, which contains doors, seats and handles.

<u>3) Agent-Based Social Force Approach</u>

Agents based on social forces in relation to pedestrian movement have been studied in both normal and evacuation situations. Henein and White (2005) proposed a modified-force agent-based model to study the shape of arching phenomenon, and Braun *et al.* (2005) simulated virtual crowds using physical and psychological forces. The High-Density Autonomous Crowds (HiDAC) model was developed to address the issue of high population density simulation by using agent characteristics and various social forces (Pelechano *et al.*, 2007). Finally, Lin *et al.* (2006) presented a crowd evacuation system based upon a social force dynamics model to study human behaviour in crisis situations.

2.5.5 Comparisons of Different Modelling Approaches

To select a suitable modelling type for developing an evacuation simulation in this thesis, different modelling approaches are compared and discussed in this section. In summary, cellular automata models use if-then functions on each cell to present an overall pattern of movement, social force models use different forces to drive movement, and agent-based models use characteristics and interactions of agents to simulate movement.

As Section 1.3 mentioned, this thesis aims to develop an evacuation model that simulates the interactions of people, fire, objects and its environment in order to understand an overall pattern of evacuation movement. Individuals' evacuation movement is unique, because they plan their movement in terms of their characteristics, knowledge and behaviour, and they might change their decisions through the interaction with others. These phenomena were found in actual fire disasters (see Section 4.3.2). In order to simulate evacuation movement that is influenced by individual evacuation decisions, agent-based modelling is considered the most suitable type of model as it can easily establish unique characteristics and behaviour of individual agents.

In addition, route selection is considered as one of the key elements of evacuation in order to understand how occupants move in a fire disaster. In cellular automata models, route selection is calculated before the simulation starts, so the behaviours such as re-planning the routes or change ability due to changes occur in an environment are not considered (Pelechano and Malkawi, 2007). In social force models, it might be difficult to identify a route path due to occupants vibrate unnaturally in high-density crowds (Pelechano *et al*., 2007). Pedestrian movement in agent-based models can be flexible by moving according to the pre-calculated paths (Szymanezyk *et al*., 2011) or dynamically calculating a new path (Treuille *et al*., 2006).

Table 2-2 displays the strengths and weakness that were reviewed in previous works (Bonabeau, 2002; Gloor *et al*., 2004; Robertson, 2005b; Pelechano and Malkawi, 2007; Zheng *et al*., 2009). Cellular automata models design simple rules on each cell and the condition vary according to the adjacent values. This modelling approach provides simple and fast calculation, but limits the interactions and movement of agents. Social force models that use forces to drive occupants move in an arbitrary direction improve the realism of pedestrian movement. However, this approach limits the density of crowds due to collision avoidance (Section 3.2.3). Agent-based models capture emergent phenomena through the interactions of agents, but side effects of its advantages occur when simulating a large number of agents.

Table 2-2 Comparisons of different modelling approaches.

Models	Strengths	Weaknesses
Cellular Automata Models	• Computational complexity • Fast and simple to implement • Strong expressive power to represent many collective behaviours	• Lack realism for high density • Limit occupant movement • Not allow for contact between agents • Rules are defined only locally and there is no specific routes that can be associated with on-going entity
Social Force Models	• Effective memory usage • Consider high-pressure characteristics • Occupant moves in an arbitrary direction	• Lack realism for high density • Oversimplified the process of pedestrians’ way finding through the traffic flow
Agent-Based Models	• Capture emergent phenomena • Provide a natural description of a system • Presumption of equilibrium is not required • Flexible	• Consider as highly sophisticated cognitive models • Demand of memory and processor of the computer

For the purposes of understanding how individuals behave and influence the results of an evacuation in this thesis, the agent-based approach has the advantage of capturing emergent phenomena of interactions between pedestrians, obstacles, doors and fire. In addition to pedestrian behaviour, fire and doors can also be defined by as individual agents in agent-based models in order to change their behaviour (variable) during the evacuation procedure. For example, a door is blocked by fire. To conclude, the agent-based approach is identified as the most flexible and suitable modelling approach for this thesis.

2.6 Navigation Algorithms

Another important aspect of evacuation modelling is navigation algorithms, which are used to calculate pedestrian movement in an environment. Van Wezel (2005) states that navigation calculations consist of three phases: pre-processing, path finding without pre- and post-processing phases, and post-processing. The pre-processing method creates a pre-generated roadmap (weighted graph) when an environment is fully known, path finding calculates a path between the current location to a known target position, and post-processing steps adapt calculated paths to achieve better results.

Overmars *et al.* (2008) introduces the shortest path search and the potential field approaches are the two common methods used for navigation in practical models. Similar to Van Wezel's first two definitions, the potential field approach uses potential distance, which is calculated between coordinates and predefined waypoints (Varas *et al*., 2007; Pelechano *et al*., 2007), and the shortest path search approach is used to find a path between two nodes (Foudil, 2009).

To select a suitable navigation algorithm for grid-based evacuation models, this section introduces four typical algorithms in the shortest path search approach and the potential field approach. Examples of each calculation can be found in Appendix A. After that, a modification of navigation algorithms is proposed based on the comparison of these algorithms and the identification of existing issues.

2.6.1 Shortest Path Search Approach

The shortest path search method deals with the issues involved in finding the shortest distance from the current location to a destination. The space is often generated by a pre-defined weighted graph, and edges are connected to nodes (locations) in order to show the connections between different locations. A number of algorithms addressing this issue and associated evaluations have been studied and reviewed (Cherkassky *et al*., 1996; Cormen *et al*., 2001; Demetrescu *et al*., 2009). This section introduces Dikjstra’s algorithm and the A* algorithm that are used for path finding in various fields.

1) Dijkstra’s Algorithm

Dijkstra’s algorithm addresses the shortest path issue by producing a tree of nodes and edges on a graph; it calculates the single shortest route between every two nodes in terms of distance costs (Dijkstra, 1959). This algorithm is used in the applications of pedestrian navigation (Wang *et al*., 2011), transport routing and networks (Jacob *et al*., 1999; Yin and Wang, 2010), water-resources analysis (Djokic and Maidment, 1993) and transitive functional analysis of gene expression (Zhou *et al*., 2002). Figure 2-14 displays the path-finding calculation steps.

```
I.    Read nodes and distance values on a graph
II.   Mark all nodes as unvisited nodes and mark distance cost on each node as
      empty
III.  Set the starting node as current node and distance cost as 0
IV.   While (the final target node is unvisited)
  {     Set current node as visited node
        Calculate distance cost from current node to its unvisited neighbour
  nodes
        If distance cost is empty or lower than previous calculation, then update
  the value
        Assign the node which is unvisited and has the lowest distance cost as
  current node
  };
V.    Identify the path from the final target node to the starting node
```

Figure 2-14 Pseudo code of Dijkstra's algorithm

2) A* Algorithm

The A* algorithm is a generalisation of Dijkstra’s algorithm described by Hart *et al.* (1968), using a distance-plus-cost heuristic function to determine a selection of grid cells for an optimal route (Gao and Xu, 2008). This algorithm is commonly used for the calculation of pedestrian navigation (Höcker *et al*., 2010), mobile robots (Bennewitz *et al*., 2002), transport networks (Jacob *et al*., 1999) and game applications (Khantanapoka and Chinnasarn, 2009; Xu and Zou, 2011).

The distance-plus-cost function is $f(n) = g(n) + h(n)$, where $g(n)$ represents the cost of a path from the starting point to any vertex *n*, and $h(n)$ represents the heuristic estimated cost from vertex *n* to the goal. Furthermore, heuristic function is categorised into three types of distance calculations, as displayed in Figure 2-15, and the pseudo code of the A* search algorithm is described in Figure 2-16.

- Manhattan distance, which only moves in horizontal and vertical directions.
  $h(n) = Gridsize \times \left(|current.x - goal.x| + |current.y - goal.y|\right)$
- Diagonal distance, which replaces one vertical and horizontal distance with a diagonal distance.
  $h(n) = \sqrt{2}Gridsize \times h\_diagonal(n) + Gridsize \times \left(h\_straight(n) - 2 \times h\_diagonal(n)\right)$
  Where $\begin{matrix} h\_diagonal(n) = min\left(|current.x - goal.x|, |currenty - goal.y|\right) \\ h\_straight(n) = |current.x - goal.x| + |current.y - goal.y| \end{matrix}$
- Euclidean distance, which is the ordinary and shortest distance between two points with unlimited angle directions.
  $h(n) = Gridsize \times \sqrt{(current.x - goal.x)^2 + (current.y - goal.y)^2}$

(Figure removed for copyright reasons)

Figure 2-15 Three types of heuristic function
Source: Amit's Game Programming Site (Patel, 2012)

```
I.    Create an open list of nodes, which contains only the starting node
II.   Create a closed list of nodes, which is empty
III.  Set the starting node as current node
IV.   While (current node is not the final target)
  {   Move current node to the closed list
      For each neighbour node (which is not in the closed list)
      {   Calculate h, g, and f value of the neighbour node
          If (neighbour node is in open list and calculated g value is lower)
              Update the neighbour node with the lower g value;
          Else if (neighbour node is not in open or closed list)
              Add the neighbour node to the open list and set its g value;
          Update f value.
      }
      Consider the best node in the open list to be the next current node: the
      node with the lowest f value or lower h value if f values are the same
  };
V.    Identify the path from the final target node to the starting node
```

Figure 2-16 Pseudo code of the A* algorithm

2.6.2 Potential Field Approach

Potential field, which is also called the flood fill approach, is a translation of distance between cells and pre-defined waypoints. The distances in static floor field are calculated before the simulation starts, so the paths are not influenced by time or other factors during the progress. This calculation approach is often used when an environment is known and fixed so the objects will rarely change between time steps (Gloor *et al*., 2004; Lu *et al*., 2010; Guo and Huang, 2011). A potential table, which records a value of potential distance on each grid cell, is fixed in an environment, so the following introduce two common calculation methods to show the efficiency of flood fill algorithms.

1) Recursive Flood Fill Algorithm

This algorithm calculates a distance cost for each grid cell from the final destination to every possible node. Figure 2-17 displays the pseudo code of the Recursive Flood Fill algorithm, which checks all cells in an array and updates the distance cost if the value is smaller than the previous calculation. This algorithm is often used for image processing, but some of the applications are found in way finding. For example, Brogan and Johnson (2003) simulated human walking paths based on the Recursive

Flood Fill algorithm by limiting the heading direction in order to reduce unnatural turns. A team from University of Porto developed a robot to challenge different mazes in the competition from the 2008 CiberMouse@RTSS competition (Azevedo *et al.*, 2009).

```
I.   Set the priority of searching directions; for example: west, north, east, south,
     north-west, north-east, south-east and south-west
II.     Set the target node as current node
III.    While (the area has an unvisited node)
 {     Set current node as visited node
       Calculate distance value of neighbour nodes
       Update to a lower value if necessary and set it as an unvisited node
       If (next node on the same direction is unvisited)
                  Set next node as current node
       If (a searching direction is not available)
                 Change to the next searching direction
       If (all neighbour nodes are visited)
                 Return to a previous node where its neighbour nodes are not visited
 };
IV.     Create a potential map with the lowest value on each grid cell
V.      Identify the path from the starting node to the final target node
```

Figure 2-17 Pseudo code of the Recursive Flood Fill algorithm

2) Priority Queue Flood Fill Algorithm

The Priority Queue Flood Fill algorithm starts from the final destination, which is the same as the Recursive Flood Fill algorithm, but it selects the lowest distance cost to prioritise nodes. A queue-based implementation of the flood fill algorithm is similar to the shortest path algorithm, because both algorithms previously visit a cell with the lowest distance cost. The pseudo code of the Priority Queue Flood Fill algorithm is displayed in Figure 2-18. Simmons *et al*. (2000) and Geraerts and Overmars (2007) computed optimal paths for robot navigation based on priority queue flood fill algorithm.

I. Set the target node as current node

II. While (the area has an unvisited node)

{ Set current node as visited node

Calculate distance value of neighbour nodes

Set the same lowest distance costs in the priority queue

Assign the queuing nodes as current node

};

III. Create a potential map with the lowest value on each grid cell

IV. Identify the path from the starting node to the final target node

Figure 2-18 Pseudo code of the Priority Queue Flood Fill algorithm

2.6.3 Comparisons of Different Algorithms

The calculations for Dijkstra’s algorithm, the A* algorithm, the Recursive Flood Fill algorithm and the Priority Queue Flood Fill algorithm were introduced in the previous two sections. In order to identify a suitable navigation algorithm for an evacuation modelling, a comparison of these four algorithms is discussed in this section.

Comparisons of navigation algorithms are found in various studies. With regard to the shortest path search approach, Soltani *et al*. (2002) evaluated the path performances of Dijkstra's algorithm and the A* algorithm. According to their findings, both Dijkstra's and the A* algorithms produce similar shortest path finding results, but the direct search towards the target by the A* algorithm reduces the searching space and decreased the time complexity. Van Wezel (2005) says that Disjkstra’s algorithm finds potential shortest paths from a starting point to all other nodes, but this algorithm is computationally expensive due to redundant searches. On the contrary, the A* algorithm is relatively fast and less complexity than Dijkstra’a algorithm as it usually calculates a single path with minimal distance. He further concludes that the A* search algorithm is the best choice for most (static) environments.

In the potential field approach, the implementation of the Priority Queue method was about 2000 times faster than the Recursive Flood Fill algorithm in an area of 50×50 cells (Gloor *et al*., 2004), and Stucki (2003) showed the Recursive Flood Fill algorithm requires more time and a greater number of cell checks than the Priority Queue Flood Fill algorithm. The reason this calculation is faster because of the first calculation step of the Priority Queue Flood Fill algorithm already identifies the lowest cost, whereas the Recursive Flood Fill algorithm checks cells repeatedly.

The algorithms of the shortest path search approach and the potential field approach are compared separately in each navigation approach, but the comparisons between the shortest path search approach and the potential field approach cannot be found in the literature. The main difference between two types of navigation approaches is identified in terms of their calculation methods, which their calculation directions are in opposite ways. The shortest path search approach calculates distance values of adjacent cells from an individual starting position to a selected destination. Another approach, the potential field approach, calculates a distance cost from a final target to every cell in the space, and a potential map is created after all cells are assigned with lowest distance costs.

To examine the efficiency, complexity and flexibility of navigation calculation, the four algorithms are compared in the following categories: the number of visited cells, the number of calculation steps, and the number of potential routes. Therefore, statistics are displayed to show the differences between four algorithms in five different configurations (Figure 2-19).

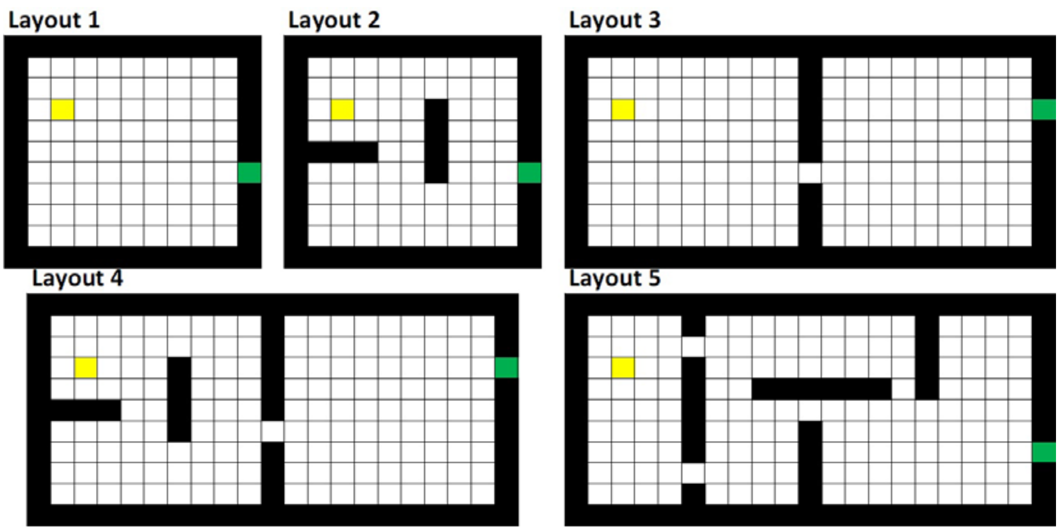


Figure 2-19 Calculate potential paths from current location (yellow cell) to an exit (green cell) in different configurations: (1) simple room; (2) simple room with obstacles; (3) two rooms; (4) two rooms with obstacles; (5) complex room

Table 2-3 displays the results of the different calculations. In general, the shortest path search approach has less number of visited cells and calculation steps when identifying an individual's path. The A* algorithm spends the least number of calculation steps and visits the least number of cells to identify a single shortest path. Both Dijkstra’s algorithm and the Priority Queue Flood Fill algorithm identify routes by visiting the same number of cells (all the available cells in space) and using the same number of calculation steps, but Dijkstra’s algorithm calculates a collection of routes while another only has a small number of paths. The Recursive Flood Fill algorithm that repetitively calculates cells to ensure every cell has the lowest distance cost is considered an inefficient calculation, because many cells are visited more than twice and some cells are visited more than five times. In these cases, the number of visited cells is often much more than the number of cells of the configuration.

To conclude, the A* algorithm is considered to be the most efficient algorithm when compares to the others. The Recursive Flood Fill algorithm, in which the number of calculation steps is about 10-30 times greater than the A* algorithm, is determined as a redundant calculation.

Table 2-3 Results of the four different algorithms in different layouts

Algorithms / **Layout and Results**	**Shortest Path Search Approach**		**Potential Field Approach**	
	Dijkstra's algorithm	A* algorithm	Recursive Flood Fill algorithm	Priority Queue Flood Fill algorithm
Layout 1: empty room (11×11 cells)				
Number of Visited Cells	82	9	266	82
Number of Calculation Steps	275	55	1750	275
Number of Potential Routes	56	1	1	1
Layout 2: simple room with obstacles (11×11 cells)				
Number of Visited Cells	75	17	134	75
Number of Calculation Steps	227	74	789	227
Number of Potential Routes	8	1	2	2
Layout 3: two empty rooms (21×11 cells)				
Number of Visited Cells	164	50	359	164
Number of Calculation Steps	553	219	2361	553
Number of Potential Routes	6720	1	1	1
Layout 4: two rooms with obstacles (21×11 cells)				
Number of Visited Cells	157	50	227	157
Number of Calculation Steps	505	193	1400	505
Number of Potential Routes	960	1	2	2
Layout 5: complex room (21×11 cells)				
Number of Visited Cells	151	26	413	151
Number of Calculation Steps	464	131	2455	464
Number of Potential Routes	375	1	1	1

2.6.4 Selection of Navigation Algorithms and Issues Identification

As noted, there is a lack of literature addressing comparisons between the shortest path search approach and the potential field approach. Although brief comparisons are discussed in the previous section, additional tests for more occupants and complex scenarios are required for simulating fire evacuations that often contain crowds instead of one individual.

In addition, the potential field approach calculates a distance cost for each cell for the whole environment once and pedestrians select routes based on this potential table, whereas the shortest path search approach calculates routes individually from each of the individual standing locations to the final target. Therefore, the complexity of the shortest path search calculation may increase if many occupants are introduced to the model.

To determine which the most suitable algorithm to simulate evacuation movement is, both navigation approaches are suggested to be developed in the model. The A* algorithm and the Priority Queue Flood Fill algorithm from each navigation approach are selected in terms of the efficiency, which reduce about 3.5-5 times of the calculation steps in the complex scenario.

Both algorithms calculate the same path, so pedestrian agents follow the same trajectory if they stand on the same starting point for each run. To prevent the outcomes of egress selection and total evacuation time being influenced by the issue of fixed route selection, two navigation algorithms are modified before inclusion in the model. A review of the literature did not identify any previous attempts to resolve this issue for these algorithms. Therefore, an idea for modification comes from Dijkstra's algorithm, which selects a path from a range of calculated routes (Section 2.6.1). According to the principles behind Dijkstra's algorithm, a potential route is identified in terms of the lowest distance cost from the final target; the algorithm searches a path from the final target to the individual starting location by following the available directions from each node. Therefore, all the potential routes have the same number of steps and are the same length.

As a result, this thesis proposes a modified calculation method to increase the flexibility of pedestrian movement in a static environment, using additional steps and directions for each cell when calculating distance costs, and in which a pedestrian's movement is determined by step numbers and directions instead of the calculated costs. This method helps the algorithm to identify a route more efficiently, and thus increases the possibility of multiple route selections rather than following the same trajectory. In addition to the static environment, pedestrian agents will re-identify their routes from the current location to simulate the changes of pedestrian movement in dynamic crowds (Section 4.4). The details regarding the modification of the A* and Priority Queue Flood Fill algorithms are introduced in Section 6.3.

2.7 Chapter Summary

This chapter reviewed literature about developing evacuation simulations. Firstly, it has been established that two main methods, the usage of video recordings and questionnaires, are commonly used to study human behaviour. Secondly, a list of evacuation behaviour and evacuation phenomena is identified from the real-life experiences and various applications of existing evacuation models. In addition, human characteristics that influence navigation and evacuation behaviour in simulations have been defined. Following that, a number of evacuation modelling approaches and navigation algorithms is introduced and compared. Finally, the agent-based approach is considered as an ideal model for this research, and two navigation algorithms (the A* algorithm and the Priority Queue Flood Fill algorithm) are selected to be modified and implement in the model.

3. Developing Research Questions

Introduction and Background	Contents of Evacuation Modelling	Developing Research Questions	Developing an Evacuation Model	Simulation Outcomes	Discussion	Conclusion and Further Work
Ch. 1	Ch. 2	Ch. 3	Ch. 4, 5 and 6	Ch. 7, 8 and 9	Ch. 10	Ch. 11

3.1 Introduction

The previous chapter introduced the main aspects of evacuation modelling, including the study of evacuation behaviour, the types of modelling approaches and the calculation of navigation algorithms. Many evacuation models have been established for research purposes or used in commercial applications, however, a number of issues are identified and should be solved in order to achieve better simulation results.

This chapter introduces a number of issues with regard to previous research and the potential impacts on simulation results. In addition, potential limitations and solutions while addressing these issues are discussed. Following that, research questions are established in terms of the selected issues with a focus on modelling human evacuation behaviour and pedestrian movement. Finally, criteria of evacuation modelling are defined to validate if the model can be categorised to a type of modelling purposes.

3.2 Identifying Research Issues

This section introduces the issues that are present in the existing evacuation models and identifies some difficulties in terms of modelling limitations or lack of information provided. The issues are classified into four categories in the following sections.

3.2.1 Issue 1 – Modelling Human Evacuation Behaviour

Modelling human psychology or physiology is a difficult task, as individuals behave differently due to personal characteristics, knowledge, feelings and many other personal factors. For example, pedestrian walking speeds differ in terms of ages, gender and floor environment according to various evacuation studies that were summarised by L. Shi *et al.* (2009), and tiredness might also reduce walking speed and cause bottlenecks during an evacuation (Pelechano and Malkawi, 2008). During an evacuation, familiarity with the exits and layouts of a building can be highly related to route choice behaviour (Benthorn and Frantzich, 1999; Kobes *et al*., 2010b).

Modelling evacuation behaviour based on traditional experiments, which have used empirical evacuation drills to understand how humans behave during an evacuation

(Guo *et al*., 2012; Cheng *et al*., 2009; Olsson and Regan, 2001), might lead to unrealistic results and thus they should not be used as the standard for assessing the simulation results of evacuation models. Although unannounced evacuations have been studied to simulate real situations (Shields and Boyce, 2000; Kobes *et al*., 2010b), these kinds of experiments cannot represent a real emergency. This is because participants might behave differently when they feel in danger and specific behaviours could only be observed in real disasters, such as people jumping from windows to flee fire (BBC, 2012). Therefore, human behaviour should be studied from emergency evacuation in real disasters instead of evacuation drills in order to understand realistic evacuation decisions and movements when people suffering a disaster.

Another issue is related to modelling time delays in the pre-evacuation period, which people usually take longer time to exit than the time indicated for an evacuation process. Pre-evacuation time varies in terms of different behaviours and activities, such as some people would try to collect valuables, ignore fire alarms or undertake other activities. Although Zhao *et al.* (2009) used a post-fire survey to identify the fact that human characteristics (education level, gender and age), building characteristics (the usage of the building) and fire characteristics (the spread of flame and smoke) were the main factors of causing time delay in pre-evacuation processes, modelling pre-evacuation time remains a big challenge in evacuation models. The difficulties of predicting the length of pre-evacuation time and the lack of information which cannot provide an accurate picture of pre-evacuation activities could influence the results of the model.

The location of occupants and the fire could influence the method used to escape a building and the time taken. For example, people on floors affected by fire and those who are in safer locations might make different decisions when choosing whether to fight the fire or evacuate immediately (Zhao *et al*., 2009). However, few discussions about pedestrian location were found in the literature while Chu and Sun (2006) pointed out that it is difficult to establish an occupant's location when a fire occurs. In addition, it is difficult to trace deceased back to the position they were in most of the disasters. As a result, most of the existing evacuation models distribute virtual occupants randomly or assign them to specific area if known.

3.2.2 Issue 2 – Modelling Pedestrian Movement in Grid-Based Models

Pedestrian movement includes navigation and egress selection. One of the pedestrian navigation approaches in crowd dynamics is called spatially discrete movement; the space is normally divided into cells with equal size and shape. Therefore, it leads an occupant to move to a cell in either a lateral or a diagonal direction (Zhang and Chang, 2011). This type of grid-based model may result in unrealistic movement (Xue and Bloebaum, 2008) as in reality people do not walk as if standing on a grid cell. As discussed in Section 2.6.4, both the shortest path search approach (A* algorithm) and the potential field approach (Priority Recursive algorithm and Flood Fill algorithm) calculate the same results of fixed routes, resulting inflexible route choice behaviour. In addition, their calculation often returns a shortest length (a diagonal distance instead of two lateral distances) in a 45-degree direction until it meet walls or obstacles (grey lines in Figure 3-1), but pedestrians normally walk as a straight path toward the corner and exits (red line).

(Figure removed for copyright reasons)

Figure 3-1 Routes in grid-based models, identified based on values that were calculated from the potential field and the shortest path search approaches (grey), and the potential routes that people move toward an exit (red) (adapted from Pelechano and Malkawi, 2008)

A similar issue happens in egress selection, which is the final destination of individual movement. For example, the usages of stairwells or exits in simulations sometimes show a long queue of occupants on one staircase/exit and other empty staircases/free exits during an evacuation. This caused by occupants selecting their destinations or stairwells in terms of the shortest distance (Pelechano and Malkawi, 2008). As a result, pedestrian egress selection is usually a fixed result as they always walk toward the nearest target, thus influencing the overall evacuation time due to bottlenecks around some exits caused by occupants who would not search for alternative paths to escape from the environment.

Another problem is the size of pedestrians, which is normally defined based on average human body size (Section 2.4). Grid-based models usually assume that one cell can only be occupied by one individual, so a different cell size might influence individual movement, egress selection and computing time. For example, a smaller size of grid cells increases the realistic of movement but requires more calculation steps to identify a path. However, the decision of cell size to represent an individual is questioned, because people who carry bags or with disabilities (Figure 3-2) require larger spaces to navigate the area and might move differently to able adults. In these cases, two people with a body size of $0.5m^2$ can pass through a metre-wide door at one time, but only one can exit if a larger body size is established. In Xue's model (2009), these types of people are represented as being the same size as others, but characteristics such as movement speed and pre-evacuation time are changed. Consequently, the accuracy of pedestrian movement might be less akin to reality.

(Figure removed for copyright reasons)

Figure 3-2 Different spaces of usage required by disabled people (Axelson *et al*., 1999)

3.2.3 Issue 3 – High Density Simulation

Pedestrian density is the number of people who occupy a space of one metre squared. According to the Green Guide, which is a UK government funded book providing detailed guidance to ensure the safety of spectators in sports grounds, a density of four people per square metre of an available standing area is the maximum permitted for safety in sports grounds (DCMS, 2008). Congestion occurs when the capacity of standing areas reaches about 4.7 persons/m^2 and people can still move slowly when it arrives at a higher density of 7.4 persons/m^2 (Zhang *et al.*, 2007; Vassalos, 2004). Under extreme conditions, a density of 15 persons/m^2 was observed by a video recording in a train station (Ando *et al.*, 1988, cited in Lee *et al.*, 2003).

These statistics display the volume of crowds that is possible in an area; hence, simulating these high densities of crowds in models has become a challenge. In grid-based models, a cell is restricted to one person, so the size of grid cells limits the maximum pedestrian density. For instance, maximum density is four persons per m^2 if a cell is 0.5 m by 0.5 m, so higher densities cannot be simulated. If simulating evacuation movement using the continuous space approach, for example, social force models (Section 2.5.2), the shape and size of human body occupied the space are more flexible.

However, continuous space approach can be restricted by the limitations of space, because pedestrians could only move around to avoid other pedestrians and obstacles rather than overlapping; thus, gridlock happens when people cannot move around freely in high density areas (Lu, 2007; Lakoba *et al.*, 2005). Figure 3-3 simulates passengers board and alight a bus during peak hours using social force models. People cannot move due to limitations of space, so people who try to alight are obstructed by those who try to board and those who stay on the bus. This causes compression and deformation rather than effective displacement found in such types of models, and it can be even worse in higher density simulations.

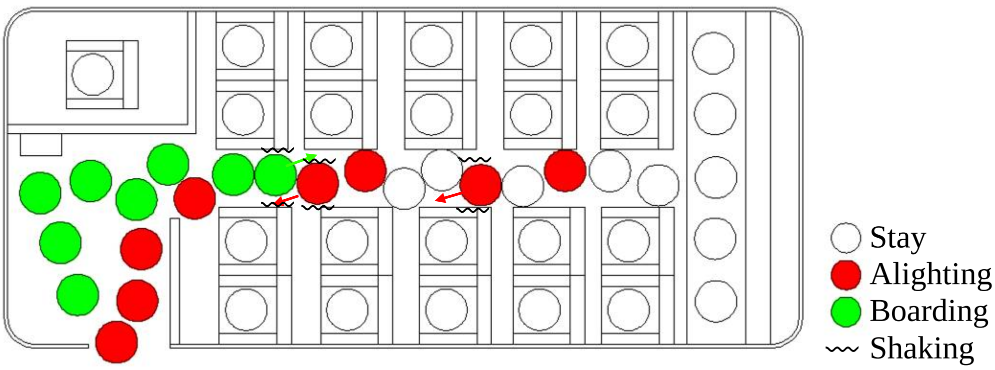


Figure 3-3 Using a social force model to simulate limitations of space on a bus during peak hours

3.2.4 Issue 4 – Modelling Human Response in High-Rise Buildings[7]

One of the most well-known disasters was the terrorism that took place on September 11th in 2001, when suicide attackers used passenger jets to crash into the Twin Towers (110 storeys) of the World Trade Centre complex in New York City. Prior to this, another evacuation of the same building took place because a bomb exploded in the underground garage on 26 February 1993. In order to examine these two serious disasters, Proulx and Fahy (2003) compared questionnaires from the 1993 evacuation with first-person statements from the 2001 evacuation in order to understand occupant response and behaviour in the World Trade Centre. In their conclusion, various improvements, such as evacuation training, were made to the buildings after the 1993 evacuation and thus contributed to a successful evacuation as a result of the 9/11 attack for most occupants. Based on the lessons from the most recent attack, additional suggestions were provided for high-rise buildings, including wider stairwells, refuge areas and fire protected lifts, to improve the safety issues.

Modelling evacuation in high-rise buildings becomes a challenge, because humans on a higher floor behave differently compared to those who occupy a lower floor. For example, evacuation models generally simulate occupants evacuate via an exit on the ground floor, but in real life, people who stay on an upper floor tend to evacuate to the roof and be rescued by helicopters instead of moving downstairs or being rescued by aerial ladders.

A number of issues which would subsequently influence human behaviour in high-rise buildings were identified from various studies after the World Trade Centre terrorist attack (Galea and Blake, 2004; Kobes *et al*., 2008). They highlighted that more factors need to be taken into consideration when disasters happen in a high-rise building as compared to a lower storey building. These factors include occupant response time, individual location, pre-evacuation actions, communication devices, collection of personal items, assessment of incident, travel speed, interaction with fire fighters, usage of lifts, group behaviour, response of fire wardens and fatigue issues.

Recently, various studies have focused on individual concepts in high-rise buildings, such as occupants in stairwells, travel speed from upper storeys and fatigue issues (Peacock *et al*., 2009; L. Shi *et al*., 2009; Pelechano and Malkawi, 2008), rather than

[7] A high-rise building is defined as a structure divided into regular floors, with an architectural height of between 35 and 100 metres, or a minimum of 12 floors (Emporis Standards, 2009).

considering an overview of all the factors in one model. Although these studies have provided useful insights into this big issue, there is still a lack of information about the impact of comprehensive issues in a high-rise building. As a result, combining different aspects of studies to simulate realistic evacuation processes in a high-rise building has become one of the most challenging tasks.

3.2.5 Summary of Issues Impact on Evacuation Models

The aim of evacuation modelling for realisation and prediction purposes is to produce accurate and realistic evacuation simulation results, such as evacuation time and risk area identification, in order to provide guidance on building configurations, fire regulations and evacuation plan for human safety. In addition, realism of evacuation movement and egress selection is also an important factor in relation to evacuation process and human safety. Table 3-1 shows a summary of the identified limitations and the influences they might exert on evacuation models.

Despite of the issues occur in grid-based models, this thesis uses grid cells to represent pedestrian human body size because of grids provide a clear arranged and fixed spatial structure, which the calculation of grid cells is simple in terms of a maximum eight fixed neighbourhood relationships (Tischendorf, 1997). In addition, this thesis simulates not only pedestrian movement but also fire movement; most of the extant fire models use grid-based approach to simplify the spread of the fire and smoke (Chiba *et al*., 1994; Muzy *et al*., 2003; J. Shi *et al*., 2009). Although the continuous space approach could provide more accurate geo-locations of each object due to decimal places representation of coordinates, this type of models (such as social force models) is generally used for one simulation instead of multiple runs (Castle *et al*., 2011) and suffer from poor computational performance (Chooramun *et al*., 2011). Every disaster is unique and therefore the results of every disaster vary, so the results of evacuation models should vary in every simulation run. To validate if the model is suitable for prediction and realisation purposes, multiple runs should be simulated to include any possibility that might happen in real-life disasters.

Table 3-1 Potential issues and their influence on evacuation simulations

Issues		Description	Impacts
Modelling Human Behaviour	Human psychology and physiology	Walking speed is affected by age, gender, environment and other health issues. Route choice behaviour is affected by the familiarity of buildings.	Accuracy of evacuation time Realism of egress selection
	Simulate human behaviour in terms of evacuation drills	People behave differently when they feel they are in danger.	Realism of egress selection Accuracy of evacuation time and risk area identification
	Pre-evacuation time	Pre-activities and individual behaviour could delay evacuation time.	Accuracy of evacuation time
	Unclear occupant location	Individuals might decide their evacuation route based on the distance from exits or conditions of an area.	Accuracy of risk area identification Realism of egress selection
Modelling Pedestrian Movement	Navigation	Most grid-based models always calculate pedestrians moving along the shortest path, and occupants in continuous models can be limited by available space and cannot overlap or switch with others.	Accuracy of evacuation time Realism of movement
	Egress selection	Occupants always move to the nearest target around them.	Realism of egress selection Accuracy of evacuation time
	Size of pedestrians	Different types of occupants move differently according to their body size. Smaller cell size models improve walking trajectories but increase calculating steps.	Accuracy of evacuation time Realism of movement Processing speed
High Density Simulation	In grid-based models	Grid size limits the maximum density.	Accuracy of crowd density
	In continuous models	Simulation might stop due to very high pedestrian density, as people cannot move freely and overlap each other.	Realism of movement
Modelling Human Response in High-Rise Buildings	Including occupant response, travel speed, group behaviour…etc.	Occupants behave differently in higher buildings. Building elements (stairs and lifts) influence individual evacuation process.	Accuracy of evacuation time Realism of egress selection

3.3 Issues Prioritization

Evacuation models are generally developed based on experience of various fire disasters or evacuation drills, but a lack of information and the difficulties of data collection and data analysis lead to a decrease in the accuracy of output results. However, the term "realistic" is difficult to define, because a fire disaster cannot be repeated and the pattern of results checked; for example, distribution of deaths. It is rare to have the same results of fire disasters occur anywhere in the world due to human behaviour, environmental conditions and many other factors. As a result, simulating a real evacuation of fire events is almost an impossible task. Although simulation can never 100% reproduce what happens in real life, evacuation models are developed to replicate situations that are close to reality in order to ensure human safety in a building and prevent similar disasters in future events. Therefore, this thesis aims to simulate a more realistic representation of results by adding behavioural rules based on the analysis of fire investigation reports.

The previous section introduced four main issues that are not handled effectively in current evacuation models. However, it is impossible to solve all the identified problems within this PhD research study, so a number of issues have been selected to be addressed in this thesis (Table 3-2). The following sections explain the decision that is based on the potential methods and the limitations that might be encountered while studying or addressing these issues.

Table 3-2 Issues selected to be addressed in the model

Issues	To be Addressed in This Thesis?
Modelling human psychology and physiology	No
Studying human behaviour in terms of evacuation drills	Yes
Modelling pre-evacuation time	No
Distributing unclear occupant location	No
Pedestrian navigation movement	No
Selecting egress routes	Yes
Size of pedestrians	Yes
High density simulation	No
Modelling human response in high-rise buildings	No

3.3.1 Selecting Issues to be Addressed

The objective of this thesis is to develop a fire evacuation model for realisation or prediction purposes. To understand how human react in fire disasters, human behaviour should be studied from real fire scenes rather than evacuation drills. As mentioned in Section 2.2.3, the accuracy of using questionnaires to understand human behaviour is relatively low. In addition, human behaviour cannot be generalised from one fire disaster, but video analysis of different fire evacuations can be difficult and long time cost. This thesis thus seeks to establish an efficient method of studying human evacuation behaviour from multiple fire cases by analysing fire investigation reports (Section 4.3).

The model aims to predict accurate usage of exits, evacuation time and high-risk area for safety issues, so individual final destination (egress selection) is considered more important than the period of navigation. Previous models simulate occupants select an exit in terms of the distance, which would affect the realism of egress selection and the accuracy of evacuation time. Therefore, this thesis improves navigation algorithms (Section 6.3) and builds behavioural rules to simulate the process of evacuation decisions (Chapter 5).

The size of pedestrians in evacuation models influences processing speed, pedestrian movement, and the number of people passing through a door. Since this thesis decides to use grid-based approach to develop the evacuation model (Section 3.2.5). Human body size (grid size) is built based on that of a normal adult, because normal adults comprise the largest group in most cases. However, the size of normal adults can vary, so different body sizes should be tested to check the relationships and interactions between people, obstacles, fire, smoke and doors. Therefore, this thesis develops two different grid sizes (0.5 m^2 and 0.3 m^2) based on an adult's shoulder to shoulder size and the depth of a human body (Section 2.4) to identify a suitable size of human for evacuation simulation.

3.3.2 Reasons and Potential Solutions for Excluded Issues

Since this thesis cannot solve all the existing issues, the issues that will not be addressed in this thesis are discussed in this section. The reasons of not selecting the issues can be grouped into three main categories: the difficulties of data collection, the complexities of modelling and calculation, and the limitations of knowledge or equipment. Furthermore, some potential solutions are proposed

Human psychology and physiology are the studies of the human mind and body. Interviews and observation are common methods used to understand the human mind, but the accuracy of interviews is considered relatively low (Section 2.2.3). The mechanical, physical and biochemical functions of humans can be studied by scientific experiments, but this is difficult to achieve due to the limitations of medical knowledge and equipment here. However, human behaviour should be studied from happened disasters or real-life scenarios, but experiments that involve fire and smoke are high risks to human safety and should not be permitted.

Pre-evacuation time can be analysed by CCTV, which records the time of individual activities. The point at which individuals start to evacuate influences pedestrian flow and causes gridlock in an area, so it is important to create a distribution of pre-evacuation time in evacuation models. However, the pre-evacuation process can be influenced by many factors such as human, building and fire characteristics, according to post-fire surveys (Section 3.2.1). These factors are too complex and too variable in every fire disaster because of different groups of occupants and various conditions of environment involved, so pre-evacuation was excluded from the evacuation model developed by this thesis.

Pedestrian movement is influenced by the location of the occupants and spread of fire. The accurate location of the individual can be observed from video recordings, but a video camera has a limited range that cannot cover the whole space in a building and it might take a long time to check an individual movement if an area is covered by a number of video recordings. Although individual locations might influence pedestrian movement and evacuation flow, this thesis simulates random distributed people with multiple runs to ensure all the space are covered and thus to simulate any situation that might occur at different locations of the building.

Pedestrian navigation movement in evacuation models is calculated by navigation algorithms. The simulation of natural pedestrian movement is a challenging task because people do not walk in a lateral or diagonal direction as found in grid-based models, nor follow the shortest distance calculated between two points. Studies of pedestrian movement record people moving in both normal and emergency situations and navigation algorithms work to improve pedestrian movement. However, the importance of movement is relatively low since this thesis aims to simulate an overall pattern. The results will be recorded or calculated after agents reach their final destinations, for instance, overall evacuation time, exit usage, distribution of deaths and risk area identification.

Simulating occupant density might be restricted by the size of grids that is designed for one standing person in some of the grid-based models, and therefore the maximum density of one metre squared is limited. In addition, people who have disabilities occupy different size of spaces to able adults. A potential solution is that a person should not be restricted to a cell, meaning a change to a different grid-polygon with smaller grids, as Figure 3-4 displays. Therefore, the density can increase from four people (body size 0.5 m × 0.5 m) to more than six people (body size 0.3 m × 0.5 m) in a one metre squared space. However, issues occur due to the irregular shape of the human body; for example, how to avoid human body overlapping with other objects, how to manage the complexity of calculation, and what shape a body is when people are moving in a diagonal direction. This thesis is not focusing on individual choices or movement but aims to simulate macro level behaviour and patterns, so human body shape is simplified to an equilateral square to reduce the complexity of calculation in the model.

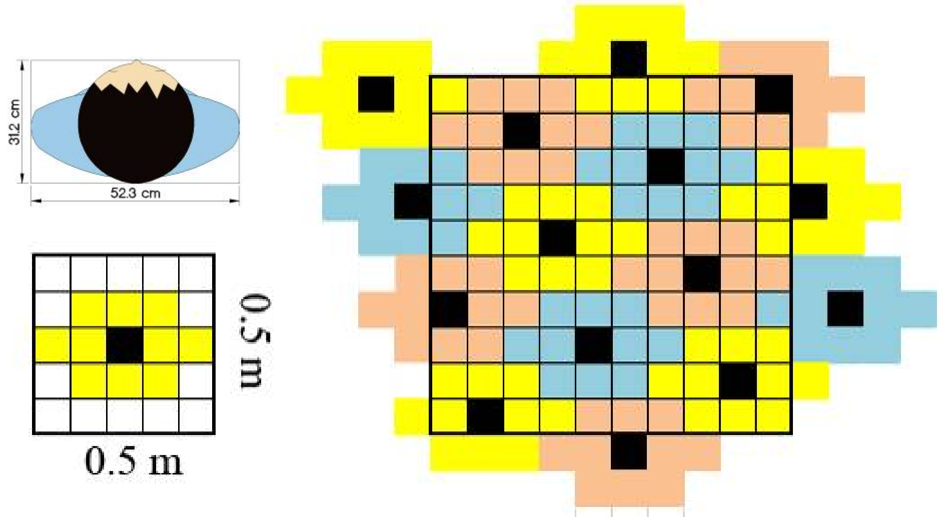


Figure 3-4 Pedestrian density using a 0.3 m × 0.5 m human body size

Various human behaviours occur in high-rise buildings that differ to those encountered in lower-storey buildings or one-floor spaces. For example, pedestrian travel speed on stairs, fatigue issues when people travel downstairs from an upper floor area and the usage of lifts. These factors could influence the situation on each floor and give a big impact to other people in the building. Nevertheless, few studies explore evacuation behaviour that are influenced by the combination of different factors in high-rise buildings can be found. This thesis thus focuses on addressing a limited number of issues due to the time restrictions and limited capability of research.

3.4 Research Questions

This thesis focuses on simulating pedestrian evacuation behaviour in fire disasters and aims to develop an evacuation model to simulate a macro level of evacuation behaviour and patterns in space (Section 1.3). This thesis proposes solutions to improve the limitation of developing evacuation models. The objective of this thesis is to answer the research questions identified below and develop an evacuation model which could produce more representative results in terms of egress selection, evacuation time and risk area identification in fire disasters.

<u>1) Modelling Human Evacuation Behaviour</u>

Kuligowski and Gwynne (2010) point out that current evacuation simulations essentially use separate "behaviour facts" instead of a complete behavioural conceptual model to simulate evacuation behaviour, so the accuracy of prediction is limited by the assumptions and simplifications of occupant behaviour. Specifically, without including human behaviour in fire exist, simulations might produce unrealistic and inaccurate results and thus provide wrong advice on building design and safety procedures. Therefore, it is necessary to understand how humans behave in real fire disasters rather than evacuation drills to improve the behavioural theory.

This thesis proposes a novel use of data, using fire investigation reports instead of traditional methods to analyse human evacuation behaviour and build behavioural rules in evacuation models. Fire investigation is an analysis of fire-related incidents; a report is produced based on information collected from a scene by an investigation team, and the report includes a determination of the origin and cause of the fire and an explanation of human behaviour. Subsequently, the evacuation behaviour studied from fire reports are used to develop behavioural rules in the evacuation model. Finally, the model is applied to real fire incidents to answer the main question: ***"Can an evacuation model be developed based on the study of fire investigation reports?"*** and the following chapters answer a number of sub-questions that are listed below.

(a) What information can be extracted from fire investigation reports to be built into evacuation models?

The contents of an official fire report are introduced in Section 4.2.2, including descriptions, observations, statements, documentations, analysis and findings. This thesis develops a generic evacuation model based on the specific evacuation behaviour and phenomena that studied from twenty different fire reports (the list can be found in Section 4.2.1). In addition, the model is applied to real fire incident based on the analysis of building information, fire location, occupancy, specific evacuation behaviour, death distribution and witness statements in the report of the selected fire incident in order to validate evacuation behaviour and movement in fire disasters.

(b) What kind of evacuation behaviour can be identified from fire investigation reports?

Most human behaviour can be found in the observations and statements sections of fire reports. Some documentations show the evidence of movement and location of deaths. Section 4.3 introduces a number of specific evacuation behaviours and evacuation phenomena that are identified in terms of three different stages of an evacuation timeline: pre-movement stage, evacuation stage, and perish stage.

(c) How can evacuation behaviour be encompassed in evacuation models?

Chapter 5 displays the framework of the evacuation model, including the timeline for the design of the simulation, the characteristics of agents and the behavioural rules developed for movement and interactions, to simulate specific human evacuation behaviour that occurred in real fire incidents (Section 4.4).

Overall, Chapter 4 introduces the contents of fire investigation reports, the resources available to fire investigation reports and methods of analysing human behaviour. Chapter 5 displays the characteristics of people, fire and door agents and the interactions between each other. Following that, the model then applies to three real fire disasters in order to validate the simulations. In Section 7.2, preliminary simulation results are used to evaluate if the evacuation model simulates the identified evacuation behaviour and phenomena, and Chapter 8 then displays the main simulation results in terms of different criteria that identified in Section 3.5. In Section 10.4, the evacuation model is validated to determine if it is suitable to realisation or prediction purposes.

2) Modelling Pedestrian Movement in Grid-Based Models

The model uses grid-based approach (Section 3.3.1), which divides the space into regular grids and the calculation is simple since there are only eight directions to the adjacent cells. When a pedestrian moves, the coordinates of each grid that the person passes through is recorded; thus, a pedestrian’s movement from a starting location to a final target can be clearly tracked. However, two issues relating to modelling pedestrian movement are identified; the first is the pedestrian movement that are calculated by a navigation algorithm, and the second is the representative size of pedestrians in an evacuation model. Both issues influence the accuracy of evacuation time and the realism of egress selection.

Therefore, different navigation algorithms and grid sizes are designed in the model to test ***"Which combination of navigation algorithm and pedestrian size simulates results that are closest to real life situations?"*** and the following sub-questions occur while developing the navigation algorithms and pedestrian size for this evacuation model.

(a) Which algorithms should be developed in the evacuation model?

Four navigation algorithms, Dijkstra's algorithm, the A* algorithm, the Recursive Flood Fill algorithm and the Priority Queue Flood Fill algorithm, from the shortest path search approach and the potential field approach were introduced in Section 2.6. As discussed in Section 2.6.4, the A* and Priority Queue Flood Fill algorithm are selected to understand whether two calculation approaches simulate different pedestrian movements or produce different simulation results.

(b) What issues do the current navigation algorithms encompass?

Both navigation algorithms have strengths and weaknesses, but one common limitation occurs while calculating a pedestrian route. Returning a single fixed route affects the results of multiple simulation runs, which pedestrian agents follow the same trajectory from a specific starting point in each run (Section 2.6.4). This issue influences the results of pedestrian egress selection and the total evacuation time.

(c) How can the limitations of current navigation algorithms be improved?

One method proposed to address the fixed route selection is the use of additional steps and directions from each neighbour square, which increases the possibility of multi-directional movement rather than merely following the same trajectory. The full steps of the modified calculation methods are displayed in Section 6.3.

(d) What size of pedestrians should be developed in the evacuation model?

Section 6.2 explains the reasons of selecting two grid sizes (0.5 m^2 and 0.3 m^2) to become the parameters of the fire evacuation model. The two different grid sizes are developed to better understanding the influences of the simulation results, and then to identify which size of pedestrians is suitable for realisation and prediction types of evacuation models.

To conclude, two navigation algorithms (the A* algorithm and the Priority Queue Flood Fill algorithm) are used for grid-based calculations in this model, and two grid sizes (0.5 m^2 and 0.3 m^2) are designed to simulate different body sizes, which affect pedestrian movement and the density of a building. Chapter 8 displays the main results of the 0.5 m^2 grid-based model, and the results of 0.5 m^2 and 0.3 m^2 grid-based models are compared in Section 9.2. Finally, the combination of a navigation algorithm and a pedestrian body size is validated and determined if it is suitable to simulate evacuation results for realisation and prediction purposes (Section 10.4).

3.5 Criteria of Evacuation Modelling

As mentioned in Section 1.3, this thesis aims to develop an evacuation model for realisation or prediction purposes, which use a third person perspective to simulate evacuation process as a macro level patterns rather than focusing on individual movement and behaviour.

Two types of evacuation models have different requirements to achieve its targets. With regard to prediction, models simulate a scene that is at the design stage before a building is built or before an event is established, meaning the configuration can be changed if necessary, according to the predicted risk areas. Realisation type of models are built to understand current issues or establish what happened in a disaster, so models simulate a scene that currently exists or has been recovered from a destroyed structure.

In order to validate the evacuation model, this thesis applies the model to real fire incidents and then compares the results to the statistics that are recorded in the fire report. This section determines three main criteria for evacuation simulations, based on the principles that were outlined in the modelling requirements of Section 1.2.

1) Realism: Egress Selection

An ideal fire evacuation model simulates realistic evacuation scenarios that have happened in real life, displaying accurate human behaviour, pedestrian movement, egress selection and the extent of the spread of fire/smoke. This thesis focuses on the realism of escape route selection, such as the number of people who evacuate through each exit, which directs occupants out of the building. Each door allows a maximum number of people to pass through in a short time, therefore, it is important to understand how people select their egress routes in case of uneven usage of doors and serious gridlock during an evacuation.

2) Accuracy: Evacuation Time and Risk Area Identification

Two important criteria, evacuation time and risk area, are commonly used to determine safety in a building. Firstly, evacuation time is the time period taken by an occupant to leave the building, and an evacuation is successful when all occupants leave before conditions in a building are considered untenable (CFPA Europe, 2009). Therefore, overall evacuation time is identified as the time taken for all occupants to evacuate safely. Secondly, risk areas in a building represent spaces that might trap people inside or locations from which people might be unable to evacuate safely during a disaster. Therefore, risk area identification could be used to suggest priority rescue decisions when fire fighters are trying to search for survivors.

3) Processing speed

Computing power is constantly significantly increasing; both computer speed and the size of memory have substantially improved in recent years and the increasing capacity helps to imitate real systems in various fields of research. For the purpose of public safety, evacuation modelling can provide an immediate or real time simulation if the processing speed is fast enough. Therefore, the model records the processing speed for each run to determine if it is suitable for real time simulation in this thesis.

However, people argued that faster processing speed (e.g. by reducing algorithm complexity) could decrease the performance of simulation results. For example, Shneiderman and Plaisant (2009, p.427) "Lengthy (longer than 15 seconds) response times are generally detrimental to productivity, increasing error rates and decreasing satisfaction. More rapid (less than 1 second) interactions are generally preferred and can increase productivity, but they may also increase error rates for complex tasks." Therefore, processing speed is not the main factor for realisation and prediction models in terms of complex calculations to achieve high quality and accuracy of results.

Summary

Evacuation models that focus on realisation purposes show the facts or histories from the real world, so the realism of simulations influences the understanding of an event. For example, the issues of pedestrian flow and congestion are influenced by the realism of egress selection. In addition, the model could highlight the usage of exits and provide reasons why a large number of deaths occurred around a particular exit. Accuracy is relatively not important for realisation; although evacuation time and risk area identification could indicate how long people took to evacuate safely and why victims died in certain areas for fire investigation purposes. These also help to indicate where the site manager should add signs or how staff should be trained to guide occupants out of the building in a short time.

Evacuation models that aim to predict accurate scenarios for future events provide results to help planners and designers to improve their construction and plan to ensure a safe environment in advance. However, it is difficult to examine human safety via experiences or evacuation drills in an incomplete building or an unhappened event. Therefore, the accuracy of the generic evacuation model plays an important role to ensure preventative measures are well-designed.

Processing speed is generally not important for both realisation and prediction types of evacuation models. However, fast calculation is sometimes used for realisation, as it allows instant messaging or sends information in a short time. For example, evacuation models could calculate potential situations in a current space, and real time simulations could provide instant information at a scene so that fire fighters could rescue people more efficiently.

Table 3-3 displays the levels of importance for each type of model, which are classified into 'very important', 'important', 'less important' and 'not important.' The simulation results in Chapter 8 and 9 are outputted in terms of these criteria. In Section 10.4, four combinations of the two navigation algorithms and the two grid sizes are compared with each other and validated by real fire incidents, using these criteria to identify if the model with one of the combination is suitable for a certain purpose.

Table 3-3 The levels of realism, accuracy and processing speed requirements for realisation and prediction types of models

Criteria / Model Type	Realism	Accuracy	Processing speed
Realisation	Very Important	Important	Less Important
Prediction	Important	Very Important	Not Important

3.6 Chapter Summary

This chapter identified four main issues that occur in the extant evacuation models. After considering the limitations and potential solutions, this thesis prior address the issues of modelling human behaviour and pedestrian movement. Based on the selected issues and proposed methods, two main research questions were established: ***"Can an evacuation model be developed based on the study of fire investigation reports?"*** and ***"Which combination of navigation algorithm and pedestrian size simulates results that are closest to real life situations?"*** The following chapters answer each sub-question that was defined in the research questions and subsequently use the three determined criteria to validate the model.

4. Analysis of Human Evacuation Behaviour from Fire Investigation Reports

Introduction and Background	Contents of Evacuation Modelling	Developing Research Questions	Developing an Evacuation Model	Simulation Outcomes	Discussion	Conclusion and Further Work
Ch. 1	Ch. 2	Ch. 3	Ch. 4, 5 and 6	Ch. 7, 8 and 9	Ch. 10	Ch. 11

4.1 Introduction

The previous chapter outlined the development of research questions, which seek to address the issues of modelling human behaviour and modelling pedestrian movement. Before developing a model to simulate pedestrian evacuation movement, the method of studying human evacuation behaviour is introduced in this chapter.

A thorough understanding of all human behaviour in every situation is impossible, because individuals are unique and may change their behaviour at different times due to their experience and knowledge even when facing the same situation. Therefore, this thesis focuses on specific evacuation behaviour that commonly occurs in fire evacuations. Traditional methods such as video recordings and questionnaires (Section 2.2.1) are widely used to study human behaviour in real life. However, a number of issues were identified regarding the use of video recordings or questionnaires (Section 2.2.3), including the difficulties of collecting data and identifying human behaviour in smoky conditions, the inefficiency of video analysis and the accuracy of questionnaires.

Another primary resource that can be collected from actual fire disasters is evidence left at the fire scene. This evidence is normally collected by a professional fire investigation team after the fire is extinguished. In addition, the fire investigation team analyses fire incidents and produces reports to explain the origin of the fire, the cause of the fire, specific human behaviour during evacuation and the issues of the building. As a result, this thesis proposes the use of a different source of data to study human evacuation behaviour in relation to fire disasters, namely the analysis of fire investigation reports, which provide a variety of information about building layout, fire circumstances and human behaviour.

The following sections include the introduction of fire investigation reports, the selected fire investigation reports, the method of analysing human evacuation behaviour, and a list of human evacuation behaviours gleaned from the fire reports. Furthermore, a number of behavioural rules are designed to simulate the human evacuation behaviours and phenomena that are selected for the purpose of this model.

4.2 Fire Investigation

Fire investigation is the analysis of fire-related incidents. After a fire is extinguished, an investigation team will explore the scene, determine the origin and cause of the fire, establish human behaviour and document the information in a formal report. There are five main reasons for fire investigation. Firstly, investigation of a specific incident helps data to be collected for forensic purposes and lessons to be learnt from the disaster, along with an understanding of how the incident happened. Secondly, the cause of fire and the loss of property are identified for insurance claims. Thirdly, the findings can be instrumental in preventing future disasters, as well as improving fire and building codes. Also, scenarios can be reconstructed for educational programmes such as safety management, risk reduction or fire prevention. Finally, fire investigation enhances knowledge and understanding of the characteristics and behaviour of the building, the fire and the occupants in order to enhance public safety in future designs.

Fire investigation is a complex and challenging task, so an investigator must possess a wide range of knowledge and skills in order to conduct it effectively. For example, fire investigators not only have to understand the science of fire behaviour, but also need knowledge of building construction, materials, electricity, mechanical devices and the effects of fire upon these materials. This enables them to reconstruct the scene in their minds or in actuality to determine the origin and cause of the fire. In addition, the investigators also require knowledge of human behaviour to forecast pedestrian movement and actions during the fire evacuation in terms of the positions of deaths and other variables.

After the fire investigation is concluded, a report is produced which usually comprises a description of the building’s site and construction, observations, statements made by witnesses or suspects, fire scene diagrams and photographs, findings and recommendations offered by the fire investigation team. The next sub-section contains a list of fire investigation reports that were collected to study human behaviour, and their general content.

4.2.1 Fire Investigation Reports

Fire reports are collected worldwide but limited to English and Chinese versions. There are more than 100 reports in relation to fire, but a limited number of reports are selected for the purpose of this study, with its aims of efficiently identifying human behaviour from the reports. Other reports were excluded due to the two main reasons. Firstly, fires that had explosion or building collapse that cut off evacuation routes as these situations are beyond the scope of the current work. Secondly, lack of information is provided, for example, missing the information of fire (location/spread of fire) and building (layout), and especially those that have no human behaviour mentioned. Therefore, only 20 fire reports are considered appropriate to this research.

The first fire investigation report, the King's Cross underground fire investigation report by Fennell's investigation team was examined. Although specific human behaviour can be found in witness statements, the report does not provide an overall layout of the station, which made it difficult to understand how human interacted in terms of the fire spread. Therefore, this thesis mainly uses fire investigation reports from the U.S. Fire Administration (USFA) as their reports have a well-structured format (Section 4.2.2) that can easily pull out human behaviour as well as other information from the fire incidents.

The USFA is an entity of the Department of Homeland Security's Federal Emergency Management Agency (FEMA); their reports usually address multiple deaths or a large loss of property, and their primary mission is to identify lessons from the fire and provide recommendations for further improvement. Other bodies also investigate fire disasters and produce reports; for example, the National Fire Protection Association (NFPA), an international non-profit organisation which seeks to reduce the worldwide burden of fire and other hazards on the quality of life. In specific cases, the U.S. National Institute of Standards and Technology (NIST) send an investigation team to determine the likely technical causes or causes of building failure; they investigated the Rhode Island nightclub fire.

Table 4-1 displays the twenty fire investigation reports that were collected from different fire investigation teams to analyse human evacuation behaviour. In addition, the type of buildings, the number of storeys and the number of total occupants, deaths and injuries that were officially recorded are also included in the table. Furthermore, each fire disaster is summarised in Appendix B.

Table 4-1 A list of fire investigation reports that were collected to study human behaviour

Title, Location, and Date of Fire Investigation Report	Building Type	Building Storeys	Total Occupants, Deaths/Injuries	Investigators	Fire Investigation Team
Investigation Report on the MGM Grand Hotel Fire Las Vegas, Nevada (21 Nov. 1980)	Commercial Building	23	≈3400 85 / ≈600	(Best and Demers, 1982)	National Fire Protection Association
Beverly Hills Supper Club Fire Southgate, Kentucky (12 May 1977)	Commercial Building	2	2400-2800 164 / 70	(Best and Swartz, 1978)	National Fire Protection Association
College Dormitory Fire Dover, Delaware (12 Apr. 1987)	Residential Building	3	180 1 / 4	(Carpenter, 1987)	United States Fire Administration
Sixteen-Fatality Fire in Highrise Residence for the Elderly Johnson City, Tennessee (24 Dec. 1989)	Residential Building	11	≈145 16 / ≈35	(Carpenter, 1989)	United States Fire Administration
Indianapolis Athletic Club Fire Indianapolis, Indiana (5 Feb. 1992)	Commercial Building	9	45-50 1 / 8	(Chubb, 1992)	United States Fire Administration
Dance Hall Fire Gothenburg, Sweden (28 Oct. 1998)	Commercial Building	2	>400 63 / 180	(Comeau and Duval, 2000)	National Fire Protection Association
Seven Fatality Fire at Remote Wilderness Lodge Grand Marais, Minnesota (12 Jul. 1991)	Residential Building	3	14 7 / 6	(David, 1991)	United States Fire Administration
Investigation into the King's Cross Underground Fire London, United Kingdom (18 Nov. 1987)	Transit Station	1 floor, under-ground	unknown 31 / unknown	(Fennell, 1988)	Department of Transport
Report of the Technical Investigation of The Station Nightclub Fire West Warwick, Rhode Island (27 Feb. 2003)	Commercial Building	1	420 100 / 230	(Grosshandler *et al.*, 2005)	National Institute of Standards and Technology

Table 4-1 continued. A list of fire investigation reports that were collected to study human behaviour

Title, Location, and Date of Fire Investigation Report	Building Type	Building Storeys	Total Occupants, Deaths/Injuries	Investigators	Fire Investigation Team
Five-Fatality Highrise Office Building Fire Atlanta, Georgia (30 Jun. 1989)	Commercial Building	10	162 5 / unknown	(Jennings, 1989)	United States Fire Administration
Nine Elderly Fire Victims in Residential Hotel Miami Beach, Florida (6 Apr. 1990)	Commercial Building	3	≈140 9 / 20	(Jennings, 1990)	United States Fire Administration
Kona Village Apartments Fire Bremerton, Washington (13 Nov. 1997)	Residential Building	4	≈150 4 / 11	(Kimball, 1997)	United States Fire Administration
Apartment Building Fire East 50th Street, New York City (11 Jan. 1988)	Residential Building	10	>56 4 / 2	(Kirby, 1988)	United States Fire Administration
Five Fatality Residential Motel Fire Thornton, Colorado (27 Jan. 1997)	Commercial Building	2	>40 5 / 23	(Miller, 1997)	United States Fire Administration
Twelve-Fatality Hotel Arson Reno, Nevada (31 Oct. 2006)	Commercial Building	4	82 12 / 31	(Ockershausen and Cohen, 2008)	United States Fire Administration
Interstate Bank Building Fire Los Angeles, California (4 May 1988)	Commercial Building	62	50 1 / 37	(Routley, 1988)	United States Fire Administration
Apartment Complex Fire, 66 Units Destroyed Seattle, Washington (21 Sep. 1991)	Residential Building	4	260 0 / 8	(Schaenman, 1991)	United States Fire Administration
Doubletree Hotel Fire New Orleans, Louisiana (19 Jul. 1987)	Commercial Building	17	>150 1 / 10	(Shapiro, 1987)	United States Fire Administration
Success Story at Retirement Home Fire Sterling, Virginia (16 Dec. 1989)	Residential Building	3	73 0 / 0	(Stambaugh, 1989)	United States Fire Administration
Chicken Processing Plant Fires Hamlet, North Carolina (3 Sep. 1991)	Industrial Building	1	≈90 25 / 54	(Yates, 1991)	United States Fire Administration

4.2.2 Contents of Fire Investigation Reports

Each investigation team presents information differently. However, reports contain common content, and this content can be classified into five categories:

1) Descriptions

Descriptions include a brief synopsis of the fire disaster and basic information regarding the fire, building and operations. A fire report starts with an overview of the fire disaster, including the date, time, name and location of the fire incident, a timeline of the spread of the fire, the number of injuries and fatalities and a summary of identifying key issues that contributed to the loss of life and property.

After a brief introduction to the fire, a section introduces the building's background including information such as the year of construction, size, materials, floor plan, overall usage and the details of construction. Some investigation teams also include the history of the building and any previous incidents that have occurred at the site. In addition, fire detection, protection and suppression systems in the building are identified if they are required to be present by local building codes.

Fire department dispatch and initial operations record details of their responses from receiving a fire alarm to the end of a fire incident. Furthermore, emergency medical services and communities who provide support on housing issues, healthcare and other necessities are sometime mentioned in a fire report.

2) Observations

Observations made by fire fighters or fire investigators explain the cause and spread of fire and human behaviour at the scene. Establishing the origin of fire is difficult, requiring fire investigators to find key evidence which is often destroyed by the fire. Afterwards, the evidence is used to identify the cause of the fire; for example, arson, accidental causes or other reasons.

Fire spread is recognised in terms of the level of damage and the observations made by fire department units at the scene. Units also identify if the fire and evacuation process is influenced by the weather. For example, a fire might occur on a hot summer day, meaning any wood in the building would be very dry, thus aiding the spread of fire (Schaenman, 1991). In addition, the weather could also influence evacuation behaviour, such as residents hesitating to go out into sub-freezing temperatures (Carpenter, 1989).

The number of occupants is established during or after the fire incident. People who stay in residential buildings or hotels can be identified according to a register, if applicable. Otherwise, an estimated number of people in a building is calculated in terms of observations at the site or an assessment of the number of injuries, deaths and evacuees.

A means of egress is an escape route that occupants might use to evacuate safely from a building. It can be determined according to floor plans or evacuation plans provided by the site. However, in some cases, exits have been found to be locked or blocked when people tried to use them during an evacuation (Yates, 1991). Fire fighters also note congestion occurs due to narrow exits and corridors (Comeau and Duval, 2000). Other issues such as furniture or equipment blocking egress routes can be identified by fire investigators after the fire. Therefore, people might not be able escape from the fire because of the conditions they face at the scene.

Observation of human behaviour is defined as the observations made by fire fighters during the period of rescuing people or fighting fire in a building. Fire fighters receive professional training to enable them to remain calm and examine the scene carefully, so they can report exact situations from a third-person objective point of view when they monitor the behaviour of occupants at the fire scene. In addition, human behaviour surrounding deaths can be identified due to investigators' knowledge and skills without the stressful impact of fleeing from the fire. Therefore, human evacuation behaviours identified by fire fighters or investigators are considered to be more accurate than witness statements.

3) Statements

A witness statement is a summary of oral evidence by a person who explains the situation in light of his/her experiences at the scene. Important statements made by witnesses are displayed in the fire reports, and details of witness interview transcripts are sometimes provided in appendices. The main purpose of the witness statement is to understand what happened in the fire and why. For instance, people might explain their feelings, the events they saw during the evacuation, the decision making process involved in the selection of their egress route, and any knowledge pertaining to how the fire started.

Witness statements can provide evidence as part of the discovery process. They can be used to recreate the scenario and figure out events at the scene. In addition, they can help officers to identify suspects if the fire is caused by arson.

4) Documentation

Documentation (diagrams, photographs and evidence) provides additional information about events at a fire scene and supporting evidence for the conclusion of the investigation. Diagrams illustrated by fire fighters show the configuration of the building, including horizontal and vertical views of floors, the topology of the surrounding streets and buildings, or a 3D simulated environment. In addition, a floor plan is often used to record the fire's origin, location of fatalities, fire apparatus at the site, or other information such as ceiling height, door size or blocked exits.

Photographs capture the view human eyes would see at the time. Fire investigators are required to take photos for evidence of factors they consider to be important. Common types of photos are attached to the fire reports, such as different views of the building, damaged areas, existing fire protection systems and the origin of the fire in order to provide evidence of their findings and support their conclusion.

Reports also record evidence collected from the building site, including the location of items that were recovered and their physical description. Researchers then analyse these items in laboratory experiments or other controlled conditions, and the resulting scientific evidence could support or reject a hypothesis about the fire.

5) Analysis and Findings

The cause of fire is identified by fire investigators, who must explain their reasons clearly when making this judgment. The cause of fire can be classified as accidental, natural, criminal or undetermined. An accidental fire is one in which ignition does not involve any deliberate human behaviour. In this case, the report has to explain the main factors surrounding the cause of the fire at a specific area or point of origin and must describe the problems that might have contributed to the fire.

Natural fires are caused by persistent chemical reactions that release heat and light without any direct human intervention. Therefore, the fire report has to explain the weather conditions or other contributory factors causing this natural fire, such as lightning, wind, humidity, heat, sparks or volcanic activity.

Arson is the criminal behaviour of setting fire intentionally or maliciously to structures or areas. If fire is considered to be criminal damage, the report has to explain the cause of arson and the reason for identification based on observations and physical evidence. Once a criminal fire is identified, police officers attempt to find the person responsible for these actions.

The cause of fire sometimes cannot be determined immediately, so the report must give reasons for this conclusion. Some potential reasons are that the flames destroyed the origin of the fire, items cannot be recovered, or not enough evidence is available to identify the cause. Therefore, further investigation might be required and the cause may be determined afterwards.

4.3 Searching Specific Human Evacuation Behaviour from Fire Reports

As described above, the contents of fire investigation reports comprise a variety of information about the fire, building, people and many others elements. The reports illustrate the distribution of deaths on a floor map as well as descriptions of human evacuation behaviour or other aspects in the text. Therefore, people are found to exhibit various behaviours in fire incidents, according to the analysis of information provided in the fire reports.

Specific human behaviour is analysed from the fire reports, using thematic analysis to classify the identified behaviour into different groups. This section introduces the analysis method and displays a number of behaviour and phenomena that occur in fire disasters.

4.3.1 Thematic Analysis

Thematic analysis is one of the most common analysis methods in qualitative research. It involves searching for themes or patterns of meaning across a data set. This method is easy and flexible to use, and it allows categories to emerge from data instead of chooses a pre-existing theoretical framework. Braun and Clarke (2006) have a clear introduction and guide of doing thematic analysis. They concluded that thematic analysis is a useful and flexible method to study psychology as well as other fields of works. Table 4-2 summarises their introduced process of thematic analysis, which is not a linear process that begins from phase one to six one after another but a recursive process that it changes the phases whenever it needs.

Table 4-2 Phases of thematic analysis (adapted from Braun and Clarke, 2006)

Phase	Process
1. Familiarising yourself with your data	Read repeatedly in order to get familiar with the data, noting down specific contents for the analysis purpose.
2. Generating initial codes	Generate initial codes for interesting features across the entire data set, documenting where and how patterns occur.
3. Searching for themes	Define potential themes and classify codes into potential themes.
4. Reviewing themes	Check the coded data and themes to ensure they support or refute the proposed questions.
5. Defining and naming themes	Describe the definitions and names for each theme.
6. Producing the report	Provide evidence of each theme using examples from the data, define the meaningful contribution that answers to the research questions, and produce the final report.

The process starts from familiarising yourself with your data (phase 1), which involves repeated reading of the data and identifying the meanings or patterns across the data set. During this phase, some potential themes or patterns are found, so the step moves to the next phase. In phase 2, codes are generated for specific features that show interests or patterns in relation to the proposed questions. Once all the data have been initially coded, search these codes at a broader level in order to classify them into themes (phase 3). The next phase (phase 4) reviews the collection of themes, sub-themes and all other coded data. It is the phase to ensure the data fits to a suitable theme and can subsequently answer the proposed questions. After all the codes and themes are established, definition and names of the themes for the actual presentation are determined in phase 5. Finally, a report is produced, including the evidence of themes within the data and the meaningful contributions that answer to the research questions.

This thesis uses thematic analysis to extract specific human behaviour from fire investigation reports. It is important to note that the whole process contains repeatedly visit different phases before the final themes decide, so Table 4-3 only displays an overall procedure of this analysis.

Table 4-3 Phases of thematic analysis for extracting human behaviour from fire reports

Phase	Process
1. Familiarising yourself with your data	Read repeatedly the 20 fire reports and write down the interesting features that are considered important to fire disasters (Appendix B).
2. Generating initial codes	Generate initial codes, including people, fire, smoke, location, evacuate, behaviour, hide, jump, room, window, exit, door, number, deaths, injuries, time, floor, building, layout, and issues.
3. Searching for themes	Define potential themes, for example people are alert to the fire when there is a clue people investigate smoke source people hide in rooms people stay near windows people fight the fire staff plays different role to guests people evacuate to main exits people are blocked by locked doors people panic people find another way out people ignore smoke/alarm people jump people are rescued through windows people use elevator people get dress or collect belongings people with movement difficulties people alert and help others people are asleep people evacuate upstairs
4. Reviewing themes	Checking the coded data and themes Classify themes to three different stages: pre-movement stage, evacuation stage, and perish stage.
5. Defining and naming themes	Describe the definitions and names for each theme (Section 4.3.2).
6. Producing the report	Provide evidence from the fire reports and define the meaningful behaviours for developing the fire evacuation model (Section 4.4).

4.3.2 Classified Evacuation Behaviour and Phenomena

Based on the thematic analysis of the twenty fire investigation reports, a number of human evacuation behaviours and phenomena have been identified. The following sub-sections introduce the results of studying human behaviour at different stages of the evacuation timeline (Figure 4-1). The timeline is based on Figure 2-2, with an additional 'perish stage', which is the period during which people are unable to evacuate successfully and die at the scene. To provide evidence of identified behaviour, the following citations of each specific evacuation behaviour or phenomenon are referred to the fire investigation reports in Table 4-1.

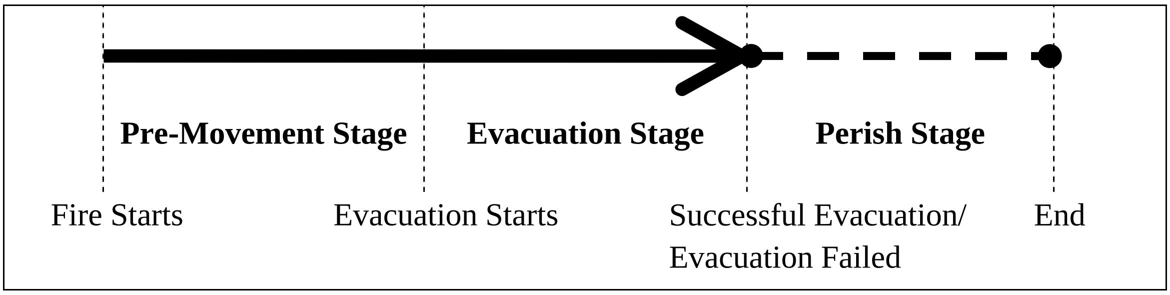


Figure 4-1 The timeline of human evacuation behaviour in serious fire disasters

4.3.2.1 Pre-movement Stage

The pre-movement stage is the period between the start of a fire alarm and the time at which an individual begins to evacuate. Pre-evacuation activities are generally identified from the descriptions of people discovering the fire and smoke, observations from fire fighters while rescuing people who delayed their evacuation, and statements made by survivors. A total of eight pre-evacuation activities were identified from the fire reports and are outlined as follows.

1) Occupants investigate the origin of the fire

People gather information by investigating the source of fire in order to determine whether an actual hazard exists or if it is a false alarm. Three different actions occur in response to unusual odours, fumes or alarms. Firstly, individuals investigate the source directly after they see or smell the smoke (Chubb, 1992; Best and Swartz, 1978). Secondly, people inform staff when they notice unusual odours (Jennings, 1990; Shapiro, 1987). Thirdly, people are alerted by alarms (Routley, 1988; Kimball, 1997).

2) Occupants start evacuating after a clue is identified

Most people lack knowledge regarding how fast the fire will spread, so they often evacuate after the fire alarm is sounded. However, some only evacuate when they see explicit signals in addition to fire alarms. For example, people may become aware of fire because they hear the commotion associated with the fire department's arrival (Chubb, 1992), see the smoke (Best and Swartz, 1978; Ockershausen and Cohen, 2008; Kirby, 1988), receive warnings from others (Kimball, 1997; Best and Demers, 1982), or notice that lights start to pop (Comeau and Duval, 2000).

3) Occupants refuse to evacuate

If too many false alarms have occurred in the past, occupants might ignore fire alarms or smoke (Ockershausen and Cohen, 2008; Schaenman, 1991; Carpenter, 1987; Shapiro, 1987; Carpenter, 1989). Some people ignore warnings from other occupants, because they believe the fire is not real (Best and Swartz, 1978) or will be under control in a short time (Fennell, 1988). In addition, people refuse to evacuate in winter, because they hesitate to go out into freezing temperatures (Carpenter, 1989).

4) Occupants fight the fire

People have various responsibilities and roles in an environment; for example, being head of a family or employees/customers in a restaurant. When people identify the source of a fire, some people choose to fight the fire to control the situation rather than take immediate evacuation (Best and Swartz, 1978; Carpenter, 1987; Best and Demers, 1982).

5) Occupants look for friends or family

People tend to gather with family members or friends to evacuate together. The interviews show that people look for their partners within the environment before they start evacuating (Best and Swartz, 1978).

6) Occupants are asleep

Many fires happen at night when people are still asleep (Carpenter, 1987; Jennings, 1990; Kimball, 1997). Therefore, people take time to wake up after smelling the smoke, receiving warnings from other people or hearing continuous fire alarms.

7) Occupants get dressed and collect valuables

Some occupants get dressed or collect valuables before evacuating, and thus fire fighters must rescue them because of this delay (Chubb, 1992). In addition, in one incident a body was found fully dressed with a flashlight on in her room, which was located near an exit on the ground floor (Jennings, 1990).

8) Employees play different roles to guests

Employees are normally well trained to deal with different situations that might happen in the environment, so they play different roles to guests. The following behaviours of staff were identified (Best and Swartz, 1978; Shapiro, 1987; Routley, 1988; Kimball, 1997; Best and Demers, 1982): firstly, employees investigate the environment in order to locate the fire and try extinguish it if possible. Secondly, employees respond by leading people to the correct evacuation routes and follow processes by giving commands. Thirdly, employees control the pedestrian flow in order to use exits efficiently.

4.3.2.2 Evacuation Stage

The evacuation stage is the period during which an individual starts to navigate the environment to find a way out of the building; it lasts until he/she evacuates successfully or unsuccessfully, which leads to the 'perish stage' (Section 4.3.2.3). Human behaviour during evacuation was mainly identified from the witness statements and observations from fire fighters when they were investigating the building and rescuing people. In addition, human behaviour before victims died was inferred by fire investigators. Based on a review of the fire reports, ten human behaviours at the evacuation stage were identified as follows:

1) Occupants evacuate through the main exits

Occupants sometimes might use an exit with which they are more familiar rather than evacuating from other exits. According to observations from fire fighters and survivors at the scene of the Beverly Hills Supper Club fire, congestion occurred at the main entrance and over half of the deaths occurred near this exit (Best and Swartz, 1978); the same was true of the Gothenburg dance hall fire (Comeau and Duval, 2000) and the Rhode Island nightclub fire (Grosshandler *et al*., 2005). This situation often occurs when the total number of occupants far exceeds the safe capacity of a building.

2) Occupants jump or wait for rescue at windows

Occupants sometimes jump from windows to flee fire or wait at windows to be rescued by fire fighters. Some people climb out or jump from windows because of the threat posed by fire and smoke; however, they risk suffering broken bones or even loss of life. This behaviour, in which occupants select windows as their egress routes, was discovered in the fire reports. For example, in some reports people appeared at windows to signal their location to rescuers and wait for help (Ockershausen and Cohen, 2008; Carpenter, 1987; Jennings, 1989; Kimball, 1997; Kirby, 1988; Best and Demers, 1982). Furthermore, some people jumped from windows when they could no longer endure the situation around them (Schaenman, 1991; Jennings, 1989; David, 1991; Grosshandler *et al*., 2005). In one serious fire disaster, a number of people were lying on the ground when the fire department arrived, and people were being defenestrated by other people behind them (Comeau and Duval, 2000).

3) Occupants find a place to hide

Some people are afraid of evacuating through smoke, so find shelter that they consider to be a safe place to wait to be rescued. Unfortunately, a number of casualties or injuries have been caused by the selection of shelter positions due to a lack of knowledge about evacuation procedures. For example, one person returned and hid under a desk after he evacuated and became confused outside his room (Carpenter, 1987). In addition, a King's Cross underground ticket officer sheltered in his office when he found the area around him was filled with smoke (Fennell, 1988). Other victims who failed to find their way out include those whose bodies were found in a far corner of the room (Comeau and Duval, 2000) or in a cooler in a factory (Yates, 1991). However, some success storeys have occurred when occupants have hidden in a room and broken the windows in order to evacuate via fire department aerial apparatus (Jennings, 1989), or stayed in their flat and waited for fire fighters to rescue them (Shapiro, 1987; Carpenter, 1989; Kirby, 1988).

4) Occupants panic when they notice rapidly accumulating smoke

Some experts opine that panic does not often occur in an evacuation, because pedestrians normally stay calm and make their decisions based on their understanding of the situation (Proulx and Fahy, 2008). This behaviour is demonstrated by witnesses of several fire disasters. For example, a group of people stayed calm in a room and waited to be rescued through windows (Jennings, 1989) and residents did not panic because they had experienced frequent evacuation practices (Stambaugh, 1989). However, on one occasion survivors mentioned that occupants moved in an orderly way towards an exit before they found thick, black smoke, then they started to rush and push others when the situation became worse (Best and Swartz, 1978; Fennell, 1988; Grosshandler *et al*., 2005).

5) Occupants search for alternative routes

Every building has main egress routes which are identified in an evacuation plan, but people do not always follow the obvious path because of different situations they encounter. For example, crowds decrease individual movement speed and limit visibility in an environment, so people may try to stand on tables to look further and seek alternative evacuation routes (Best and Swartz, 1978). In addition, they might change their original evacuation routes if an exit is found to be locked (Yates, 1991), or if they see smoke or fire in the process of evacuation (Schaenman, 1991; Carpenter, 1989). Other situations, such as occupants hiding in a room or evacuating through windows when they realise they cannot evacuate safely through an exit, are also identified as kinds of alternative routes (the sections referred to as 'occupants jump or wait for rescue at windows' and 'occupants find a place to hide').

6) Occupants escape from the fire or smoke

Human actions in relation to potentially hazardous situations show that people change their evacuation paths when smoke blocks their original egress route. The reports contain example of occupants moving to upper floors when they discovered smoke was coming from downstairs (Routley, 1988), one group of people sought refuge and used windows to escape when smoke blocked their route (Jennings, 1989), and in another incident people escaped to the other side of the corridor when they saw smoke coming from the stairwells (Schaenman, 1991).

7) Occupants use lifts during evacuation

Use of lifts is normally not permitted when a fire happens, because they might stop or breakdown during the fire. If the lift is not working, people will be trapped inside and be unable to find an alternative way to escape. Although some people have successfully evacuated from the fire by using lifts (Chubb, 1992; Kirby, 1988), many victims who failed to follow the instructions have been found in lifts (Shapiro, 1987; Routley, 1988; Jennings, 1990).

<u>8) Occupants try to break open locked exits to evacuate</u>

Many exits have been found to be blocked by stored goods or locked to prevent people getting in or out of the buildings. When an emergency situation occurred, people were forced to find other ways to escape (see 'occupants search for alternative routes'). Some people tried to kick down the locked exit to evacuate before searching for alternative routes (Yates, 1991).

<u>9) Occupants help each others</u>

People help each other when they notice the danger. People who live in residential buildings take care of family and neighbours (Schaenman, 1991), or offer support to elderly and disabled people (Kimball, 1997). Employees play different roles to guests, so they guide occupants out of the building in an efficient way (Best and Swartz, 1978; Best and Demers, 1982).

<u>10) Evacuation of disabled occupants</u>

People who have disabilities are, by definition, limited in their abilities to move around in an environment. Therefore, they require other people to help them during evacuation (Kimball, 1997). Unfortunately, victims with restricted mobility have been found at fire scenes (Best and Swartz, 1978; David, 1991; Carpenter, 1989).

4.3.2.3 Perish Stage

Serious fires often comprise intense heat and thick black smoke. Once people are exposed to this kind of environment for a long time, the smoke and heat harm the human body and thus people perish at the scene as a result. Evacuation phenomena, or evacuation results, are determined by the documentation provided in the fire reports. According to the location of deaths and the descriptions in the fire reports, some human behaviour prior to death has been identified:

<u>1) Deaths appear around an exit</u>

In serious fire disasters which involve many victims, fatalities are often found near an exit, especially if the building was overcrowded. For example, an approximate number of 400 people attended the party in the Gothenburg dance hall, which had a maximum safe occupancy of 150 people (Comeau and Duval, 2000). A large group of people (43) died near the main entrance, which was the only route to evacuate out of the building. In addition, the number of people (1200-1300) in the Cabaret Room far exceeded the capacity of occupants that could safely be in the room by almost double, and the customers were told to evacuate through two exits at one end of the room (Best and Swartz, 1978). However, the rapidity of the spread of the fire and overcrowding in the Cabaret Room caused the deaths of many victims near the exits in the fire (Figure 4-2). Furthermore, Figure 4-3 shows deaths mainly occurred along the entryway towards the front entrance in the Rhode Island nightclub fire (Grosshandler *et al*., 2005).

(Figure removed for copyright reasons)

Figure 4-2 Location of fatalities in the Beverly Hills Supper Club Fire (Best and Swartz, 1978)

(Figure removed for copyright reasons)

Figure 4-3 Location of fatalities in the Rhode Island nightclub fire (Grosshandler *et al*., 2005)

2) Deaths in a secluded room

Fire fighters have not only rescued people from a room, but also discovered victims who have become overcome by smoke or fire in a room (Comeau and Duval, 2000; Miller, 1997; Ockershausen and Cohen, 2008; Yates, 1991; Carpenter, 1987; Jennings, 1989; Jennings, 1990; David, 1991; Carpenter, 1989; Kimball, 1997; Kirby, 1988; Best and Demers, 1982; Grosshandler *et al*., 2005). In this instance, potential human behaviour prior to death was determined according to statements and evidence collected. For example, Figure 4-4 shows a group of injured and deceased people who were found in a cooler in the Chicken Processing Plant Fire (Yates, 1991). Survivors indicated there was no real evacuation plan in the factory, so a number of people went into a cooler to hide from the fire. However, the sealed door was not shut tight and thus allowed smoke into the cooler.

(Figure removed for copyright reasons)

Figure 4-4 A group of victims were found in a cooler (Yates, 1991).

Another fire occurred in a residential motel; the fire trapped occupants in their rooms since no alternative egress route was available (Miller, 1997). This was confirmed by the operator at the front desk saying that one of the occupants in Room 222 phoned reception to report that they were trapped in their room by the fire. According to Figure 4-5, Room 220 and 222 were the only rooms which only allowed people to evacuate through the door to the enclosed corridor; people in other rooms could evacuate from external walkways.

(Figure removed for copyright reasons)

Figure 4-5 Four occupants were trapped and perished in two separate rooms (Miller, 1997).

4.4 Defining Behavioural Rules for Evacuation Models

The previous section displayed a number of evacuation behaviours and phenomena that were identified by thematic analysis in terms of utilising information from the fire investigation reports. An overall 100 features relating to human behaviour were identified and were subsequently classified into different stages of an evacuation timeline. The frequency of specific human evacuation behaviour that is covered in different reports is displayed in Figure 4-6. Two significant evacuation phenomena that occurred in over 10 out of 20 fire reports are *"occupants jump or wait for rescue at windows"* and *"deaths in a secluded room."* In addition, the overall amount of behaviour that occurred in the evacuation stage (49%) was higher than the behaviour in the pre-evacuation stage (35%) and the perish stage (16%).

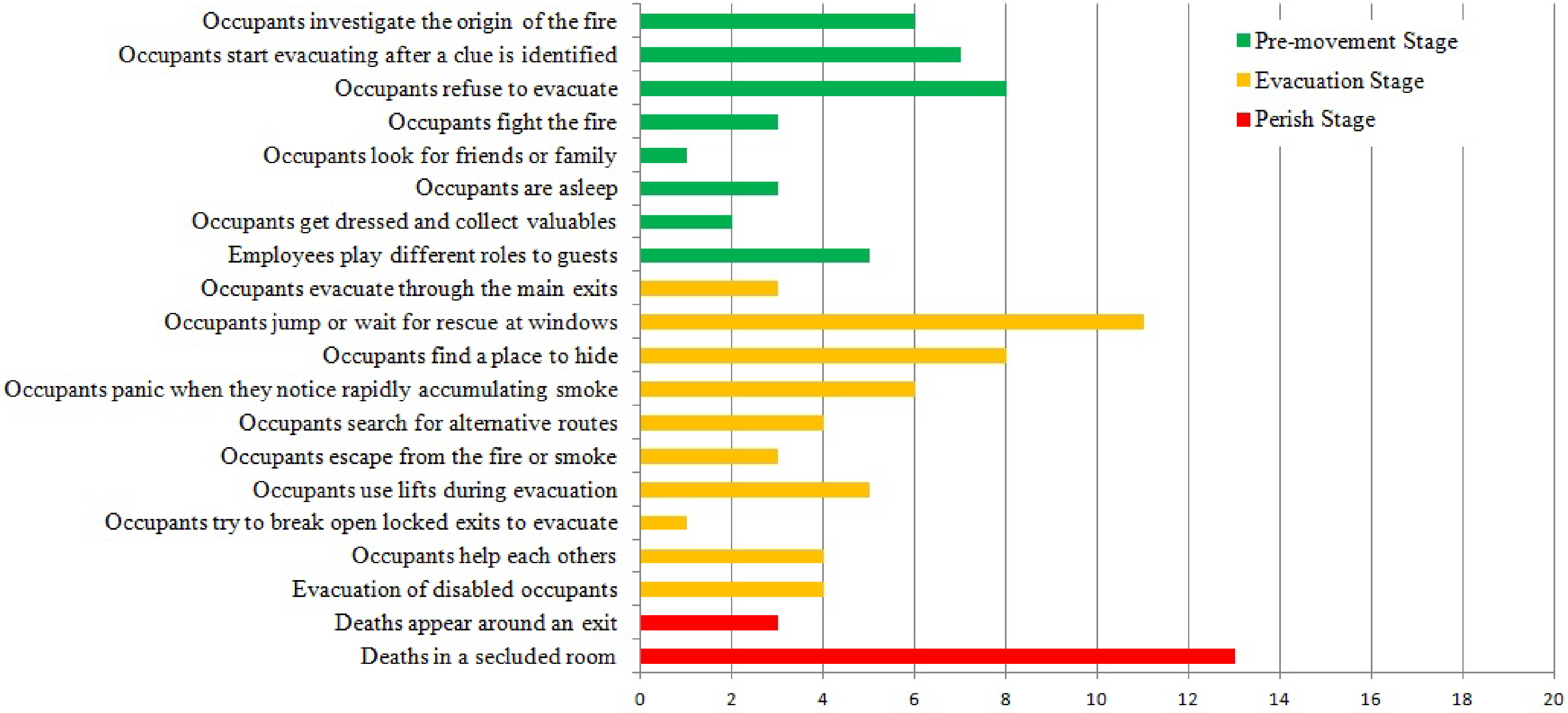


Figure 4-6 Frequency of human behaviour that occurred in the twenty fire investigation reports

As Section 3.3 described, the issues of modelling pre-movement time, human response in high-rise buildings and three others will not be addressed in this thesis. Therefore, the development of behavioural rules first exclude all the behaviour in pre-evacuation stage and the behaviour that is related to high-rise buildings, such as the usage of lift. In addition, the preliminary model considers an evacuation scenario using normal individuals' decisions, so pedestrian agents will not have group behaviour or limited by disabilities at this stage of the modelling development. Accordingly, the behaviours of *"occupants help each others"* and *"occupants evacuate with disabilities"* are excluded. Special cases of exits that do not follow building regulations and behaviour that occur in high-floor buildings are not considered, which are *"occupants kick locked exits to evacuate"* and *"occupants use lifts during evacuation."*

As a result, behavioural rules are built based on the final six selected evacuation behaviours in the evacuation stage. In addition, the model also simulates the situations of occupants perishing in a fire in order to validate the accuracy of risk area identification. The followings introduce the design of behavioural rules to imitate the identified behaviour. Furthermore, the assumptions for each behavioural rule and their potential impacts on the simulation results are presented. An activity diagram of evacuation simulation (Figure 4-7) shows an occupant's evacuation decisions in this model.

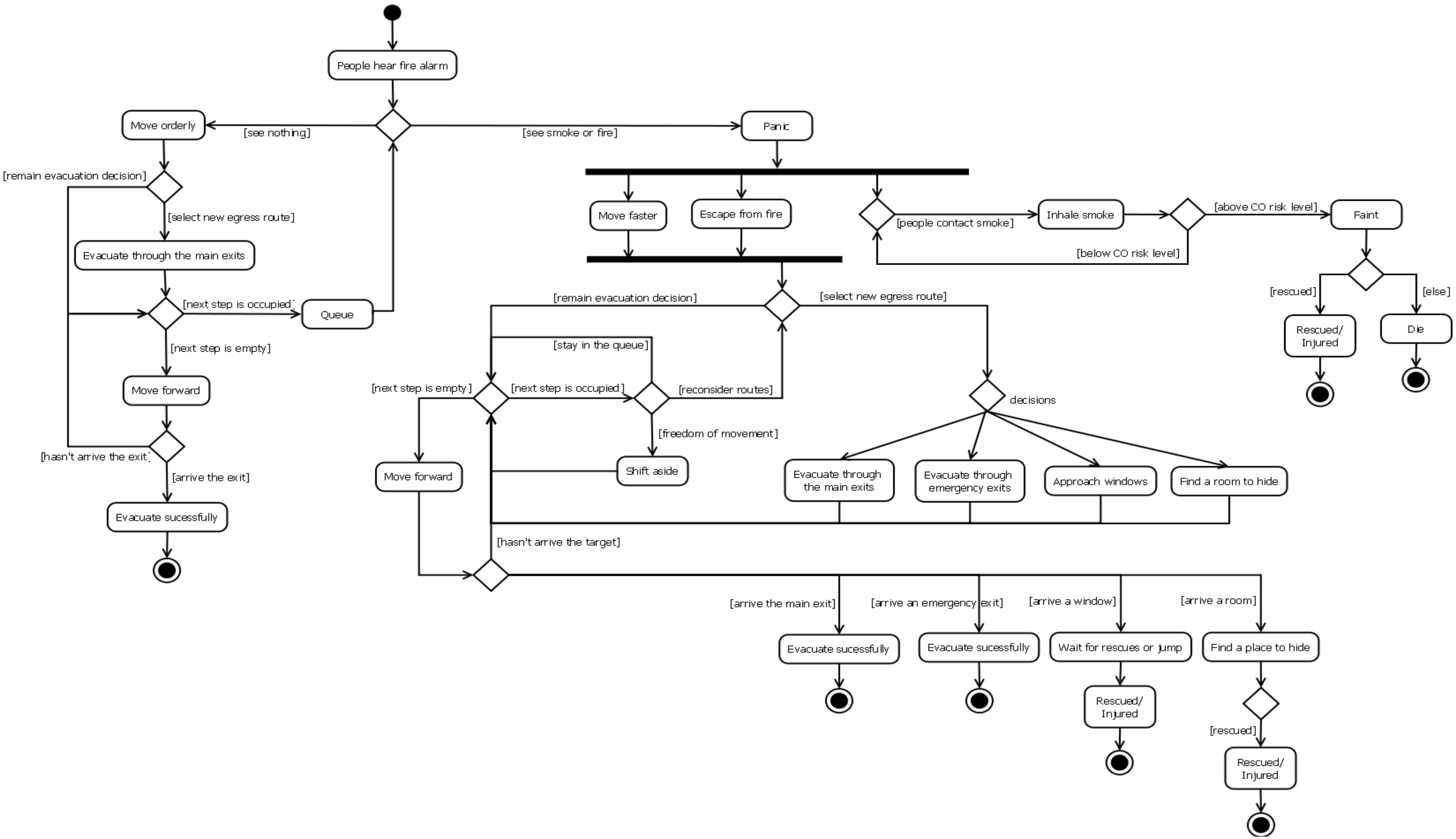


Figure 4-7 Activity diagram of evacuation decisions

1) Occupants evacuate through the main exits

The model designs that pedestrian agents move towards the main exit as their first priority before they see the fire. While people increase their potential walking speed (see behavioural rule 4: *"occupants panic when they notice rapidly accumulating smoke"*), people might decrease their actual moving speed. Section 5.4.1 explains the "Faster-is-Slower" phenomenon occurs when pedestrian agents encounter a door agent in the model. However, this behavioural rule increases the number of people who are heading to the main exit and decreases the freedom of movement for those who stuck in the middle of crowds. Therefore, it might cause an uneven usage of exits and thus influence overall evacuation time, which can potentially be longer than expected.

2) Occupants approach windows

The model assumes that all the pedestrian agents can reach the windows, and those who decided to evacuate through windows are considered to be injured and rescued by fire fighters. In addition, the model is designed for lower-height buildings, so it does not consider the situation of death if they jump. This behavioural rule increases individual choices during the selection of egress routes and estimates the number of people that might escape safely and faster than the people who are stuck at an exit. As a result, this behaviour influences individual evacuation time, and could suggest improvements to the number and design of windows based on the result of the simulation.

3) Occupants find a place to hide

The model assumes that pedestrian agents will stay at a specific location until they are rescued by fire fighters or die due to smoke inhalation, so they will not leave the room if they are in hiding position. This might increase the number of deaths in a building, because people sometimes decide to evacuate the building after examine the situations outside the room. However, this result could display the distribution of deaths and thus suggest priority rescue areas to fire fighters in terms of potential risk areas where occupants might hide. The method of people detecting a hiding space in a room is introduced in Section 5.4.2.

4) Occupants panic when they notice rapidly accumulating smoke

The model assumes that pedestrians move patiently at a normal speed and are willing to queue behind others before they see any smoke or fire. Panic begins when people notice rapidly accumulating smoke, they increase their walking speed and become impatient, so they might shift aside to jump the queue or select different routes in order to escape more quickly from the fire. The moment occupants change their behaviour is designed (Section 5.4.3), and a method to simulate people queuing or stepping on others is displayed in Section 5.4.7. This change in behaviour influences pedestrians' movement speed (Section 5.4.4) and has an impact on evacuation time.

5) Occupants search for alternative routes

This model assumes that pedestrians might change their egress routes when they queue behind other people for a long time and become impatient; the time at which this occurs is different according to individual patience levels (Section 5.3). After they change their evacuation routes, the model recalculates the route from the current location to a new final destination. As a result, individual evacuation time will vary when escape directions and movement are changed.

6) Occupants escape from the fire or smoke

This behaviour is similar to the previous behavioural rule *"occupants find alternative routes"*, but individuals change their direction according to the spread of smoke and fire. This model designs fire/smoke agents and pedestrian agents and allow them to interact with each other (Section 5.4.5). Therefore, occupants check and identify if smoke occurs on the way to their destinations based on an assumption that occupants have unlimited visibility distance. Therefore, occupants will change their evacuation routes before they reach to a selected destination.

7) Deaths and injuries occur at the scene

This phenomenon shows that it is important to simulate deaths and injuries inside a building. One of the main causes of death is smoke inhalation, so pedestrian agents are designed to inhale smoke (Section 5.4.6). Once agents inhale a certain amount of smoke, they will faint or die at the scene and need to be removed or rescued by fire fighters. An analysis of the simulation identifies high risk areas which can be suggested as priority rescue areas to fire fighters and can improve the building configuration to reduce the potential for future serious disasters.

4.5 Chapter Summary

A novel usage of different data source was proposed to study human behaviour in fire disasters, namely using fire investigation reports to analyse human evacuation behaviour. A list of specific evacuation behaviour and phenomena were identified based on thematic analysis. After that, seven main behavioural rules are designed to simulate the selected evacuation behaviour and phenomena that commonly occur during fire evacuation in lower-height buildings. To model these behavioural rules, the next chapter introduces the development of evacuation model in terms of different types of agents and their interactions with each other.

5. Model Design

Introduction and Background	Contents of Evacuation Modelling	Developing Research Questions	Developing an Evacuation Model	Simulation Outcomes	Discussion	Conclusion and Further Work
Ch. 1	Ch. 2	Ch. 3	Ch. 4, 5 and 6	Ch. 7, 8 and 9	Ch. 10	Ch. 11

5.1 Introduction

The previous chapter introduced the method of studying human evacuation behaviour using a different data source, fire investigation reports. A list of behavioural rules was designed for the evacuation model (Section 4.4). The evacuation model is developed based on the grid-based and agent-based approach. This chapter introduces the development of agents and condition rules for simulating generic evacuation behaviour.

Human and other objects such as doors and fire/smoke, which would influence behaviour or status in terms of the evacuation timeline or via interactions with each other, are defined as agents. To model the identified human evacuation behaviour, pedestrian, door and fire/smoke agents are created and assigned with various characteristics. Next, condition action rules that show interactions between various agents are designed to recreate the phenomena in fire disasters. At the end of this chapter, a number of parameters are tested using a simple configuration in order to understand how various inputs influence the results of the simulation.

5.2 Overview of the Simulation

Section 4.4 introduced the pedestrian behavioural rules that were built based on the selected evacuation behaviours and phenomena in the fire reports. This section introduces the overview of evacuation timeline and additional condition action rules that are designed to simulate the interactions between different agents. Three types of agents and their interactions are introduced in the next two sections.

Figure 4-7 shows the evacuation decision process of a pedestrian agent. At the beginning of the fire, each pedestrian agent hears the fire alarm and decides to evacuate. Next, the agent moves in an orderly and systematic fashion to the main exit if he identified no hazards. Once pedestrian agents notice the fire, the agent begins to panic and starts moving faster, jumping the queue, searching for other ways out or the safest place to stay. When the fire and smoke spread over the space, the agent would inhale smoke and receive injuries such as lung damage. In addition, the agent could faint or die at the scene or might be fortunate enough to be rescued by fire fighters.

The above evacuation process can be divided to different stages of an evacuation timeline (Figure 5-1). The first stage of the evacuation timeline lasts from the moment the simulation starts to the time when a pedestrian agent identifies the fire and begins to panic. At the beginning, pedestrian agents start to evacuate as a result of hearing the fire alarm. Pedestrian agents display calm behaviour at this stage, so they only move towards the main entrance/exit and walk at a normal speed in an orderly manner towards the exit. In addition, they queue patiently behind other pedestrian agents when finding another agent stands in front of them. Meanwhile, fire agents are spreading over the space and checking whether any pedestrian agent notices this hazard.

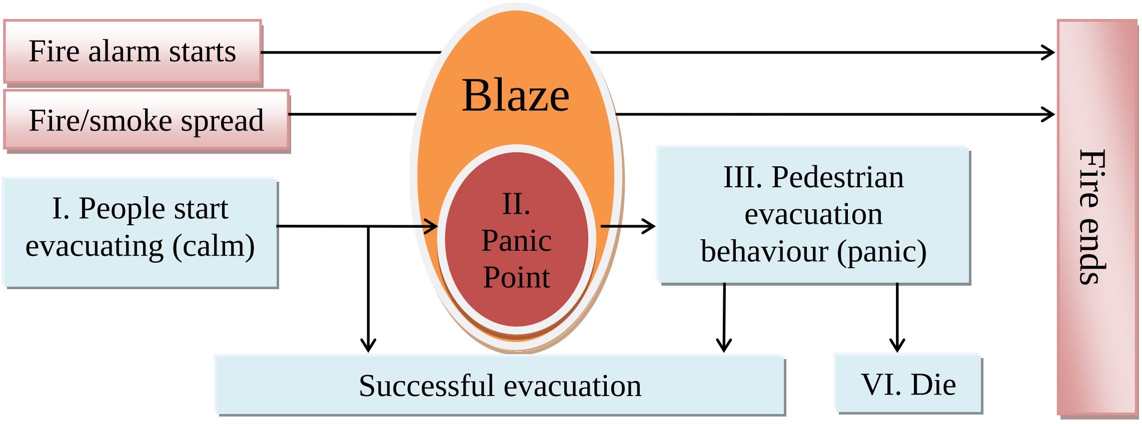


Figure 5-1 The evacuation timeline in the model

The second stage of the evacuation timeline is the moment pedestrian agents change their behaviour from calm to panic once they identify hazards, which happens at the time of seeing the smoke or fire. The model designs all the pedestrian agents share the same knowledge of noticing fire, which represents that all pedestrian agents panic at the same time based on an assumption of the first witness shout out loud to warn everyone in the space. Afterward, they begin to behave differently when they realise it is an actual fire rather than a false alarm.

The third stage of the evacuation timeline is defined as the period after all pedestrian agents panic and before any pedestrian agent start to perish. Most of the evacuation behaviours selected in Section 4.4 are simulated at this stage. For example, the characteristics of pedestrian agents change, so they increase their maximum speed of walking and decrease the level of patience. In addition, pedestrian agents avoid walking in any direction where they see fire/smoke and search for alternative routes, including going to unknown doors or known emergency exits to escape, jumping or being rescued at windows or searching for a room in which to hide. Regarding to their selection, the model assumes that pedestrian agents have a basic knowledge of the environment, which the layout is pre-defined and different types of doors is assigned to the building.

The last stage of the evacuation timeline is the period in which the fire is out of control and causes pedestrian agents who have not evacuated to faint or die. A large fire sends out thick smoke which limits individual visibility, so pedestrian agents decrease their walking speed to search for a way within a limited visible distance around them. After pedestrian agents inhale a certain amount of smoke, they might faint or die at the scene.

In addition to the behavioural rules that were designed for individual pedestrian agent (Section 4.4), Figure 5-2 shows the process and condition action rules of the interactions between three types of agents. The details of each design are displayed in Section 5.3 and 5.4.

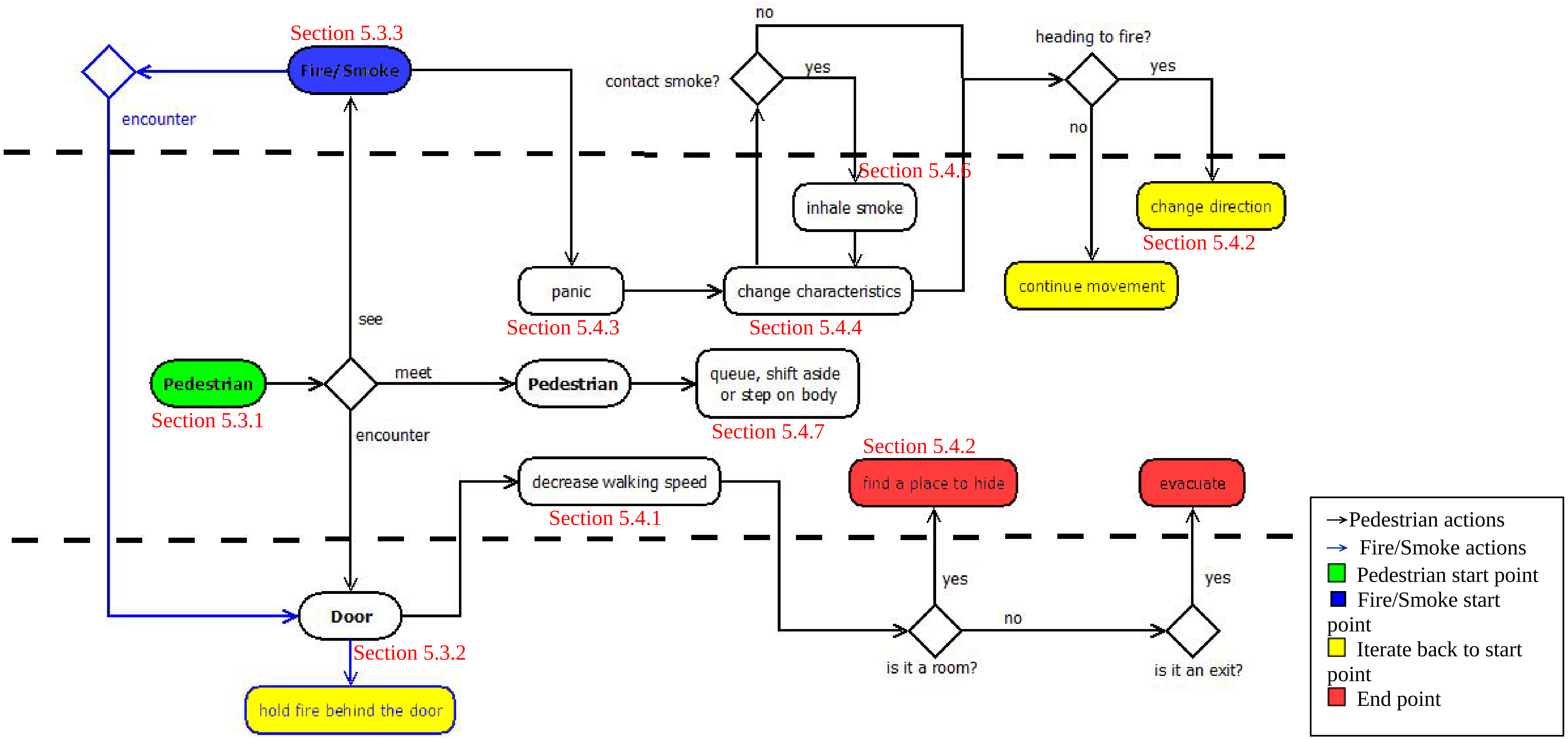


Figure 5-2 Condition action rules of the interactions between agents

5.3 Defining Agents

An agent-based model uses a set of rules to simulate virtual agents, and these virtual agents typically have the characteristics of autonomous, social, reactive and goal-directed entities. In this evacuation model, three types of virtual agents are defined. Pedestrian agents represent individuals navigating their way out of the building. Fire/smoke agents show the spread of smoke, recording spread speed and smoke level. Door agents record the type of doors and the number of pedestrian agents who pass through the door as well as control the volume of pedestrian flow at each door.

5.3.1 Pedestrian Agent

Each pedestrian agent in the model has personal characteristics, such as age, walking speed, level of patience and carbon monoxide tolerance level. Age is classified into three groups: adult (between 14 and 65 years old), elderly (over 65 years old) and children (less than 14 years old) (Section 2.4). While an individual is assigned an age, pedestrian walking speed is set to a velocity according to statistics from observations on pedestrian behaviour under unannounced fire evacuation drill conditions in mass rapid transit (MRT) stations (Yeo and He, 2009). Table 5-1 shows average pedestrian walking speeds on flat walkways in terms of different age groups and the time that pedestrian agents spend on one 0.3/0.5 m^2 grid size (Section 6.2) in real time.

Table 5-1 Pedestrian average walking velocities on a flat plan in three age groups

Age group / Walking speed	Children (under 14)	Elderly (over 65)	Adult (14-65)
Average walking speed on walkways (Yeo and He, 2009)	1.08 (m/s)	1.04 (m/s)	1.27 (m/s)
Walking speed on a 0.5m^2 grid model	0.46 (sec/grid)	0.48 (sec/grid)	0.39 (sec/grid)
Walking speed on a 0.3m^2 grid model	0.28 (sec/grid)	0.29 (sec/grid)	0.24 (sec/grid)

Next, this model simulates pedestrian aggressive behaviour, such as shift aside to jump the queue or change evacuation routes, by using different degrees of patience. A range of patience index is set as different decision time steps that pedestrian agents would change their mind when their next step is unavailable. For example, a pedestrian agent who has a patience level 10 remains at his current location and waits behind a queue for 10 steps before he changes his evacuation decision. A pedestrian agent who has a lower level of patience easily decides to shift aside or change his decision. This variable is test for sensitivity in Section 5.5.1.

Pedestrian agents die after exposure to smoke for a certain time, which is based on individual carbon monoxide tolerance levels. Carboxyhaemoglobin (COHb) is a stable complex of carbon monoxide and haemoglobin that forms in red blood cells when carbon monoxide is inhaled, and hinders delivery of oxygen to the body (Goldstein, 2008). Table 5-2 shows higher COHb levels harm human health more significantly than lower COHb levels. In the model, the carbon monoxide tolerance level of a pedestrian agent is designed to be over 50% COHb, at which individuals might faint and lose judgement or physiological control within 10 minutes, in order to simulate intense fire situations.

Table 5-2 Associated symptoms in terms of different carbon monoxide concentrations and COHb levels, provided by Goldstein (2008)

Carbon monoxide concentration	COHb level	Signs and symptoms
35 ppm	<10%	Headache and dizziness within 6 to 8 hours of constant exposure
100 ppm	≥10%	Slight headache within 2 to 3 hours
200 ppm	20%	Slight headache within 2 to 3 hours Loss of judgement
400 ppm	25%	Frontal headache within 1 to 2 hours.
800 ppm	30%	Dizziness, nausea and convulsions within 45 minutes Insensible within 2 hours
1,600 ppm	40%	Headache, tachycardia, dizziness and nausea within 20 minutes Death in less than 2 hours
3,200 ppm	50%	Headache, dizziness, and nausea in 5 to 10 minutes Death within 30 minutes
6,400 ppm	60%	Headache and dizziness in 1 to 2 minutes Convulsions, respiratory arrest and death in less than 20 minutes
12,800 ppm	≥70%	Death in less than 3 minutes

5.3.2 Door Agent

Door agents are designed to identify the usage of the exit, recording the type of door and the number of occupants who pass through the door. The type of egress exits is decided prior to the start of the simulation according to the doors which can lead occupants out of the environment and the usage of doors. The first type is the main door, which is used by most of the occupants to enter and exit the building. Based on observations of some people's real-life evacuation experiences, occupants normally evacuate through the door through which they entered or the nearest available main door (not the emergency exits) if they do not detect any risk in the environment. Another type of door is an emergency exit, which is specifically installed for emergency situations. These emergency exits are usually located in a stairwell or hallway to direct people out of their current space to a safer place. In some situations, occupants decide to hide in a room and wait for rescue. As a result, the door of a room (the third type of doors) is selected when people try to navigate a room and check if it is suitable to hide inside. Finally, the doors which are locked are set as unavailable during simulations.

A door agent records the number of occupants who pass through the door. This figure represents the number of evacuees who pass through the main exits or emergency exits. Accordingly, the model shows the usage of each exit in order to understand if an exit is installed at a suitable place so that occupants can use it efficiently during the evacuation. In addition, the number of occupants who pass through a door of room shows the frequency of people exiting or entering the door while they are navigating and finding a refuge place. Therefore, some advice about door size could be determined according to this number.

5.3.3 Fire/Smoke Agent

Fire/smoke agents, which record fire and smoke information, show the location of fire/smoke and the level of fire/smoke. The model sets the origin of the fire on a grid before the simulation starts. Despite many factors that might influence the spread of smoke and flames in a fire disaster, the model implements smoke as spreading gradually in a circular motion and flames will spread randomly to their neighbours. To simulate the spreading phenomenon, fire/smoke agents gradually spread to their eight neighbours from the original fire starting point and then permeate the whole environment. Therefore, the spread of fire/smoke agents is displayed as a water ripple, and each circle is a radius of the distance between integer cells and the central cell (Figure 5-3). Furthermore, the speed of fire/smoke agents is assigned as 0.19 m/s to 0.35 m/s according to the speed of smoke in Yu and Zhang’s model (2009). This simulation does not consider air temperature, wind, materials, oxygen levels or other factors that might influence the movement of fire and smoke. These factors can be studied in related research such as that by Oleszkiewicz (1989), Luo and Beck (1994) and

Mostafaei *et al*. (2011), or tested in real-life experiments by controlling variables to understand the influences on the spread of smoke and fire.

In addition, each fire/smoke agent records the levels of smoke and fire for visualisation purposes. Fire and smoke are integrated together to be the same fire/smoke agent in the model, and the colour of each fire/smoke agent changes according to its level to visualise the intensity of the smoke and fire. As mentioned in the previous paragraph, the model is designed to spread smoke gradually and spread fire randomly to its neighbours, so Figure 5-4 shows this phenomenon of fire spreading in a north-east direction. In Figure 5-3 and Figure 5-4 and in the remainder of this thesis, white cells represent the spaces in which there are no fire/smoke agents and the colour of each cell with an agent changes from light grey to dark gray according to the smoke level, and then finally to red if fire takes over the space.

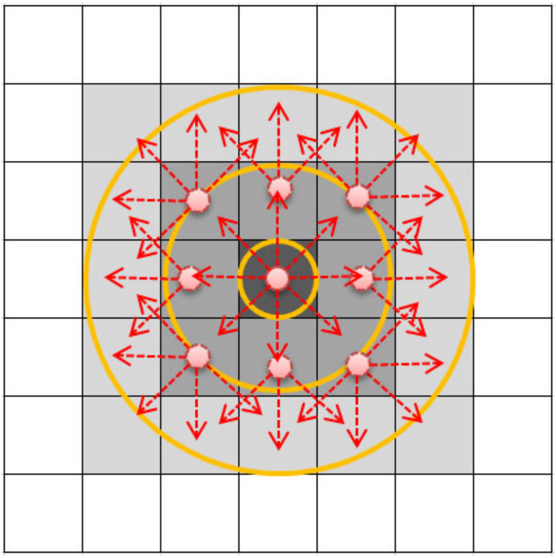


Figure 5-3 Form of spreading smoke in the evacuation model (grey: smoke; darker colour represents higher smoke level, dots: agents, red arrows: agents' potential spreading directions)

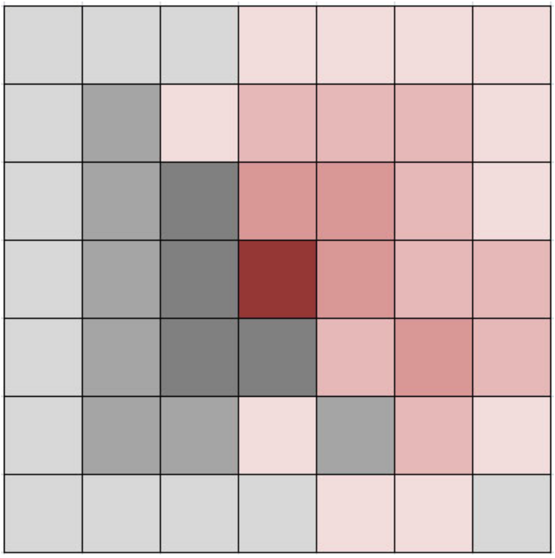


Figure 5-4 Using colours to represent the spread of smoke and fire (grey: smoke; darker colour represents higher smoke level, red: fire filled with smoke; darker colour represents higher fire level)

5.4 Interactions **between agents**

The model contains three types of agents: pedestrian, door and fire/smoke agents, and their individual characteristics were introduced above. However, simulation of evacuation behaviour is not only based on individual characteristics, but also on interactions between different types of agents. The model creates eight different interactions between pedestrian, door and fire agents to simulate the process of evacuation decision as displayed in Figure 4-7. Figure 5-2 illustrates the interactions between different agents and the details are introduced in the following subsections.

5.4.1 Pedestrian agents decrease walking speed when they encounter a door agent (Pedestrian vs. Door)

When occupants exit a door, the shape of pedestrians around the door can be identified as linear, arch or a mixture of both, as displayed in Figure 5-5. In a calm situation, pedestrians physically queue in a line and wait patiently to pass through an exit. If an emergency happens, occupants commonly rush towards an exit and stay close to the exit in an arch shape because of their desire to evacuate safely as soon as possible. A significant mixture of linear and arch shapes happens when there are too many occupants staying in the same enclosed space.

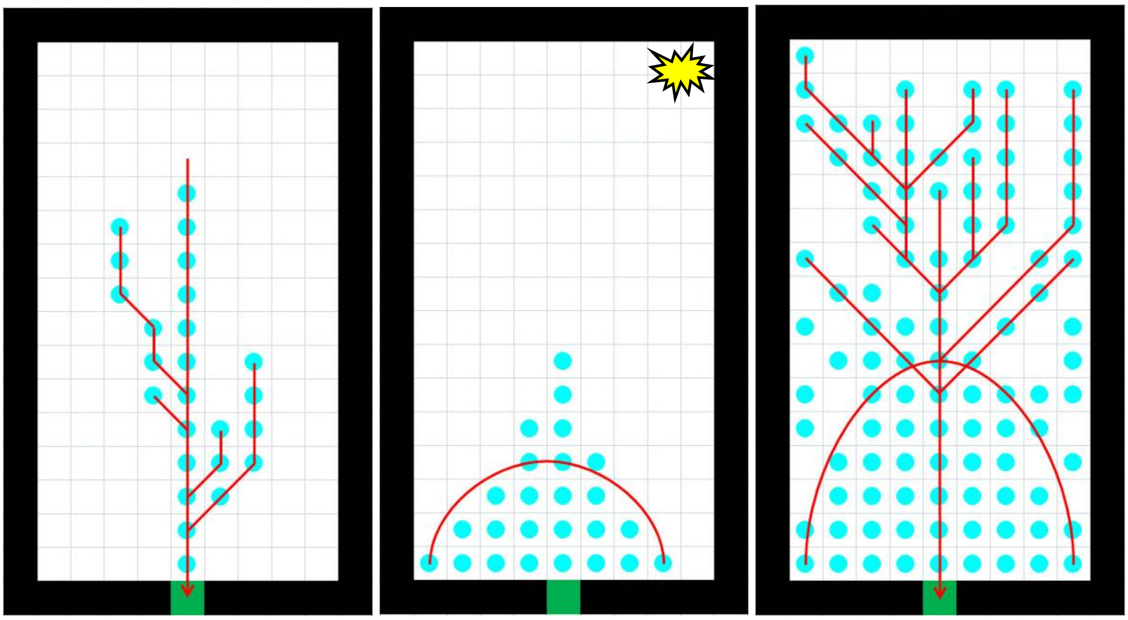


Figure 5-5 Pedestrian movement shape at an exit when people stay calm (left), panic (middle) and the space is overcrowded (right)

The model decrease their speed by about 0.4 m/s when they encounter a door agent, according to the statistics from Fang *et al.* (2004, cited in L. Shi *et al.*, 2009). When too many pedestrians are trying to pass through the same door in a short time, the speed of movement decreases and results the phenomenon of "Faster-is-Slower" (Section 2.3.2). To identify the delay time that causes this phenomenon, the model assumes pedestrian walking speed is influenced by the total number of people who are moving towards the same door. Section 5.5.2 shows the tests of this condition.

5.4.2 Defining a room and identifying a hiding place when a pedestrian agent encounters a door agent (Pedestrian vs. Door)

Dead occupants were sometimes found in a room (Section 4.3.2.3), because they thought they could avoid smoke entering the room if they sheltered in an enclosed space (Section 4.3.2.2). In order to simulate deaths in a room, the model simulates pedestrian agents searching a room and identifying a place to stay in the room. The followings outline the method of defining an enclosed room.

An enclosed room is defined by searching objects on each grid and identifying potential refuge spaces. When a pedestrian agent steps on a door agent as the type of a door room (Section 5.3.2), the calculation starts from an adjacent grid inside the door and identifies the empty grids along the wall. Figure 5-6 displays the search method in a typical room. The search changes direction if it hits a wall and continues its identification of each grid; finally, it identifies an enclosed room when the search point returns to the starting point.

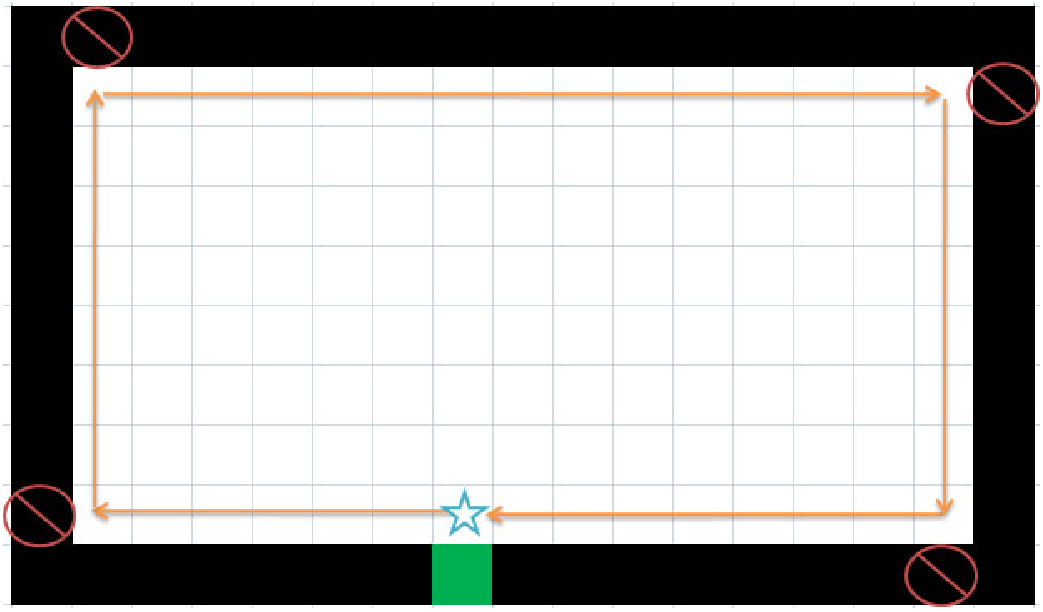


Figure 5-6 Basic room definition method: the search begins at the starting point (blue star) and changes direction when it hits a wall, until it returns to the starting point

Room identification methods for different types of room, such as a narrow space and a complex configuration, are displayed in Figure 5-7. Furthermore, the model assumes that pedestrian agents stay in a place which is close to walls. Therefore, pedestrian agents consider empty grids to be hiding places when the function detects a room along the wall, and these hiding spaces are randomly selected by pedestrian agents who want to hide in a room.

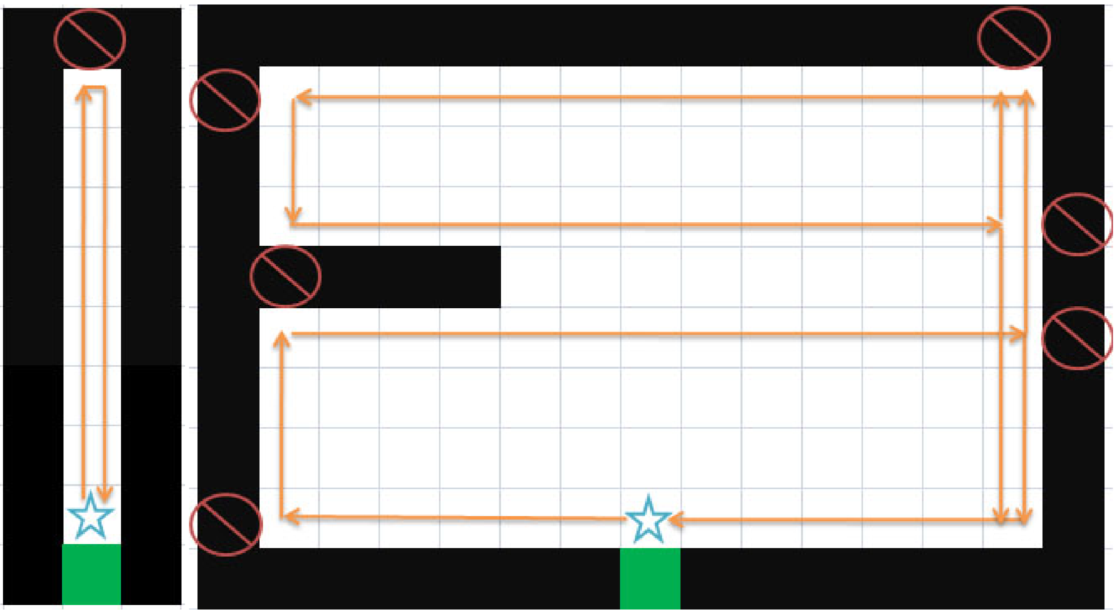


Figure 5-7 Room identification methods for a narrow space (left) and a complex configuration (right)

5.4.3 Pedestrian agents change behaviour when seeing fire/smoke agents (Fire vs. Pedestrian)

Occupants will display different behaviours after they discover a hazard, such as walking faster, becoming impatient or searching for alternative escape routes, and the model these occur at the stage of panic. To identify the moment when pedestrians change their behaviour and begin to panic, the model assumes the moment that the fire/smoke agents detect a pedestrian agent represents the point at which a person finds the fire. Rather than using a fixed radius circle for each pedestrian agent searching for fire agents, the model uses each fire/smoke agent as a central point and detects vertically and diagonally in eight directions from the central point (Figure 5-8).

The reason for using this opposite method of detection is that the model is designed to handle a large number of pedestrian agents, which far exceeds the number of fire/smoke agents that is set at the beginning of the simulation. In addition, fire/smoke agents spread gradually so that the detection method moves from one fire/smoke agent to many agents; in other words, the calculation develops from simple to complex until one of the fire/smoke agents detects a pedestrian agent. Otherwise, all the pedestrian agents would have to recalculate their visual range at every step until they detect a fire agent, and a lot of system time would be dedicated to establishing whether pedestrians discover the fire. As a result, this method reduces the large number of calculation steps.

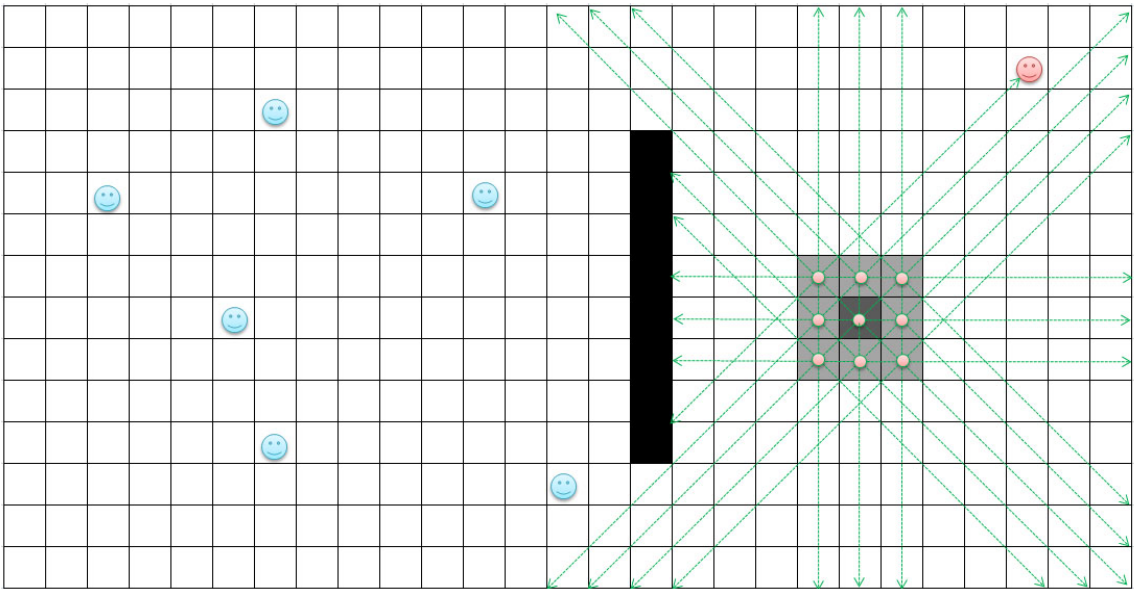


Figure 5-8 An example of fire agents detecting pedestrian agents. Once fire agents detect a pedestrian agent, the pedestrian agents will change from calm (blue) to panic (red)

Moreover, the model makes three assumptions before simulating this interaction. Firstly, pedestrian agents have unlimited visual distance, so they can see as far as possible, except for space behind an obstacle such as a wall. Secondly, some occupants turn around to check what is happening behind them, and other occupants might not realise they are in danger, even when they are close to the hazard. Thirdly, pedestrian agents communicate with each other, and thus all the pedestrian agents notice there is a fire and change to panic characteristics at the same time. For example, pedestrian agents increase walking speed or search for an alternative egress route.

5.4.4 Pedestrian agents change characteristics when encounter fire agents (Pedestrian vs. Fire)

Panic affects pedestrian behaviour when they realise that they are in real danger (Section 4.3.2.2). This section introduces the change in the behaviour of pedestrian agents after they start panicking after contact with fire agents. For example, occupants move faster in order to get out of the building safely, become impatient or slow their walking speed because of thick smoke which restricts their visibility and mobility.

The pedestrians' degree of patience changes after occupants begin to panic. In order to simulate panic situations, such as crowds jumping the queue and rushing towards an exit to evacuate faster, the model considers all pedestrian agents become impatient when panic happens. Therefore, their patience level at panic stage is 0.

At the scene of fire disasters, some occupants increase walking speed because they are trying to find a quicker way out of the environment and some remain calm and walk normally toward their destinations. According to an observational study (Willis *et al*., 2004), the highest reported speed (around 2.5 m/s) occurred when people trotted or ran in the space. Therefore, the model increase pedestrians' maximum walking speed and assumes that pedestrian agents can walk at a speed ranging from normal velocity (1.08 m/s) to faster velocity (2.5 m/s) after the timeline switches to the panic stage. Each age group of pedestrians can move about 1.7 to 2 times faster than the original speed (Table 5-3).

After a period of time, pedestrian walking speed decreases due to the smoke and fire which spread over the environment restrict pedestrians' visibility and actions. Jin and Yamada (1989) have suggested that pedestrian travel speed decreases when the smoke concentration increases and Galea *et al.*'s model (1996) used crawl rate as the maximum of walking speed to simulate occupants move slowly in smoke. Therefore, this model designs a pedestrian agent starts to inhale smoke and his mobility is restricted to a slower walking speed in terms of the experiment of walkers and crawlers (Nagai *et al*., 2006), which the speed of crawlers decreased to about 60% of the normal walking speed.

Table 5-3 Pedestrians' faster and slower walking speeds which are influenced by smoke and the time period

Age group / Original walking speed and simulation	**Children (under 14)**	**Elderly (over 65)**	**Adult (14-65)**
Original walking speed	1.08 (m/s)	1.04 (m/s)	1.27 (m/s)
Faster walking speed (after panicking)	1.08 – 2.08 (m/s)	1.04 – 1.79 (m/s)	1.27 – 2.5 (m/s)
Slower walking speed (limited visibility)	0.83 – 1.08 (m/s)	0.68 – 1.04 (m/s)	0.75 – 1.27 (m/s)

5.4.5 Pedestrian agents change their evacuation movements according to fire agents (Pedestrian vs. Fire)

A pedestrian's movement is the route from a pedestrian agent's current location to a final destination, which is dependent on evacuation decisions. This model defines that pedestrian agents only evacuate through the main entrance/exit before they identify a hazard (fire agents). In addition, the model assumes panicked pedestrian agents would select one of the four evacuation decisions based on a pre-defined percentage: evacuating through the main entrance/exit, evacuating through an alternative emergency exit, escaping through windows, or hiding inside a room. The percentages are tested and displayed in Section 5.5.3.

To simulate the way in which pedestrian agents are influenced by fire agents, pedestrian agents identify whether any fire agent is located on the way to their destinations, and they are thus aware of the fire and would change the direction of movement in advance. Two potential situations might happen when a pedestrian agent understands that there is possibly a fire blocks the route. The first is that pedestrian agents will stick to their original decisions, because this is the only evacuation route that they know could direct them out of the building; this is normally towards a familiar exit like the main entrance/exit. The second situation is that pedestrian agents change their direction to other egress routes in order to avoid direct impact from the fire.

5.4.6 Pedestrian agents inhale smoke from fire agents (Pedestrian vs. Fire)

Smoke inhalation is one of the main causes of death in fire disasters, and it is estimated that over 50% of fire deaths are caused by smoke inhalation injuries rather than burns (Cahalane and Demling, 1984). In addition, deaths caused by smoke inhalation were confirmed in eight studied fire investigation reports (Comeau and Duval, 2000; Yates, 1991; Carpenter, 1987; Jennings, 1989; Routley, 1988; Carpenter, 1989; Kimball, 1997; Schaenman, 1991). Therefore, it is important to simulate the interaction between fire, smoke and pedestrians, especially when smoke inhalation causes them to faint or die at the scene. In the model, pedestrian agents inhale smoke when they are exposed to the fire agent.

An original fire/smoke agent is located at one grid cell as the starting point of the fire, and the fire/smoke agents spread dimensionally through the environment. When the simulation starts, pedestrian agents start evacuating and walking in different directions, depending on their evacuation decisions. However, the layers of smoke soon fill the space and pedestrian agents encounter fire agents. When a pedestrian agent detects a fire agent on the same grid, the pedestrian agent starts to inhale smoke. In addition, the model designs the level of smoke would increase cumulatively and subsequently influence pedestrian accessibility and the emergency evacuation procedure. Moreover, pedestrian agents will faint if they inhale certain amounts of smoke, which are set differently based on carbon monoxide tolerance levels (Section 5.3.1), and those who fainted on the floor will have a certain possibility to be rescued (sensitivity test in Section 5.5.4). This rule is designed based on an assumption of fire fighters would enter the building and first rescue people who are seriously injured rather than people who are closest to the exit.

5.4.7 Pedestrian agents queue behind another pedestrian agent or step on a pedestrian agent who fainted or died at the scene (Pedestrian vs. Pedestrian)

Human behaviour is complex and every individual is unique, so interactions between pedestrians may be more complicated than individual behaviour. Group evacuation behaviours such as travelling together, following others and searching for friends/family, are not considered in the model due to the complexity of behaviour and modelling methods. The model mainly focuses on individual evacuation behaviour, so pedestrians select their egress routes based on individual decisions. However, the model simulates queuing behaviour to illustrate pedestrian collision detection and repulsion. In addition, stampede is simulated by overlapping between occupants if they decide to step over bodies for a faster evacuation. A stampede that is caused by the poor health of people or people pushing and falling to the floor is not considered in this version of the model.

As introduced in Section 2.3.2, queuing behaviour is classified into three types: pedestrian movement in front of a counter, pedestrian movement when passing through a gate, and pedestrian movement when getting on and off a vehicle. The second type of queuing behaviour is simulated in the model to demonstrate occupants passing through an exit and to avoid pedestrian agents overlapping each other. According to their level of patience, each pedestrian agent waits in the queue; the higher their level of patience, the longer time they will wait. Once a pedestrian agent's patience is exhausted by waiting too long, he will shift aside to pass the queue or attempt a different path from the current location.

Stampedes commonly occur at huge events such as sport stadiums (Sakyi-Addo, 2001; BBC, 2009), musical festivals (CNN, 2009; BBC, 2010) or building fires (BBC, 2006; Huggler, 2004). Occupants step over people who unfortunately fainted, died or fell down at the scene during the evacuation. The model simulates building fires, so pedestrian agents faint or die if they inhale an amount of smoke that exceeds their carbon monoxide tolerance levels. Therefore, an interaction between pedestrian agents takes place if a pedestrian agent decides to step over or pass by a body if the agent discovers a pedestrian's body lying in front of him.

5.4.8 Door agents keep fire agents behind a door (Door vs. Fire)

Doors play an important role in the event of fire, because a closed door could keep the smoke inside and provide protection for those on the other side of the door. Nowadays, fire doors, which are designed with a fire protection rating and must meet a regulatory standard, are required to be installed in buildings to prevent the spread of fire and smoke within the space. Many old buildings do not have this kind of door protection, and therefore the smoke can escape through the gap under the door if the door is not sealed. Although different buildings might have different types of door, the model assumes doors are self-closing and are not tested fire doors, which cannot hold fire for more than few minutes.

To simulate the way smoke is held by doors, the model makes fire agents stop at a door agent for 30 seconds. The accurate time it takes smoke to spread from the gap around a door has not been tested, as the time might be influenced by the size of the fire, heat and other factors. Therefore, thirty seconds is considered to be a critical time for the fire turning from a small flame into a major fire (U.S. Fire Administration, 2011) in order to notify people who are behind a door that a fire/smoke is spreading.

5.5 Sensitivity Analysis

Before testing the model with real data, the model is verified to ensure it simulates correct human behaviour and movement that are expected to occur during an evacuation. In this section, a sensitivity analysis is conducted to study how various inputs affect the uncertainty in the outputs of the model. Ideally, every parameter should be tested to identify the influence of the outputs. However, the model that contains a large number of parameters for agents, environment and fire incident (see Section 6.2) is difficult to be fully tested. Among the variety of parameters, the tested parameters are selected if they are not designed based on any previous research. The remainder of this section uses a simple configuration to test the sensitivity of different parameters, and the model is further calibrated to ensure the outputs are produced in a reasonable value from the real data (Section 7.2).

The scenario simulates 200 pedestrian agents in a 0.5 m^2 grid-based building, using a simple configuration, including two rooms, one main exit, one emergency exit and windows (Figure 5-9). The fire starts in a storage room, which is locked and inaccessible to the public. This figure shows human behaviour before they panic, with pedestrian agents evacuating toward the main exit once the fire alarm (simulation) starts. At the same time, fire/smoke agents spread gradually through the space.

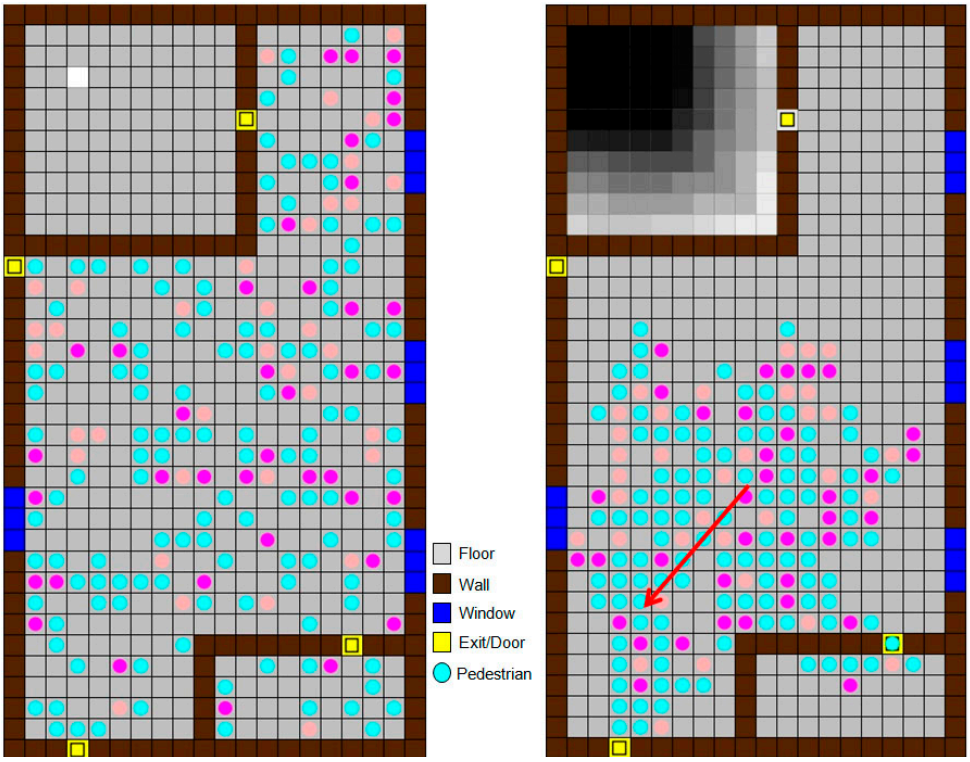


Figure 5-9 The evacuation scenario before the simulation starts (left) and the events before pedestrian agents panic (right)

Figure 5-10 displays the moment when a pedestrian agent becomes aware of the fire and thus all pedestrian agents change their behaviour to panic. When the fire pedestrian agent sees the smoke, which has just spread outside the door, all the occupants panic at the same time. The definition of panic is that pedestrian agents change their behaviour and select different evacuation methods (see Figure 4-7).

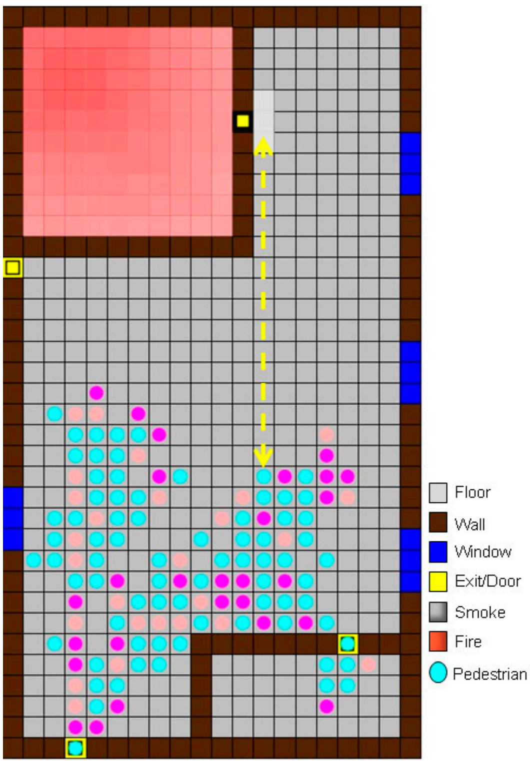


Figure 5-10 The moment when all pedestrian agents panic when seeing the fire/smoke agent

Once pedestrian agents panic, those who behave impatiently shift aside to skip the queue or select different evacuation routes. The characteristics of pedestrian agents change at this stage, so they increase their maximum speed of walking and their level of patience decreases. In addition, pedestrian agents avoid walking in any direction where they can see fire/smoke and search for alternative routes; for example, occupants go to unknown doors or known emergency exits to escape, jump or wait to be rescued at windows or search for a room in which to hide (Figure 5-11).

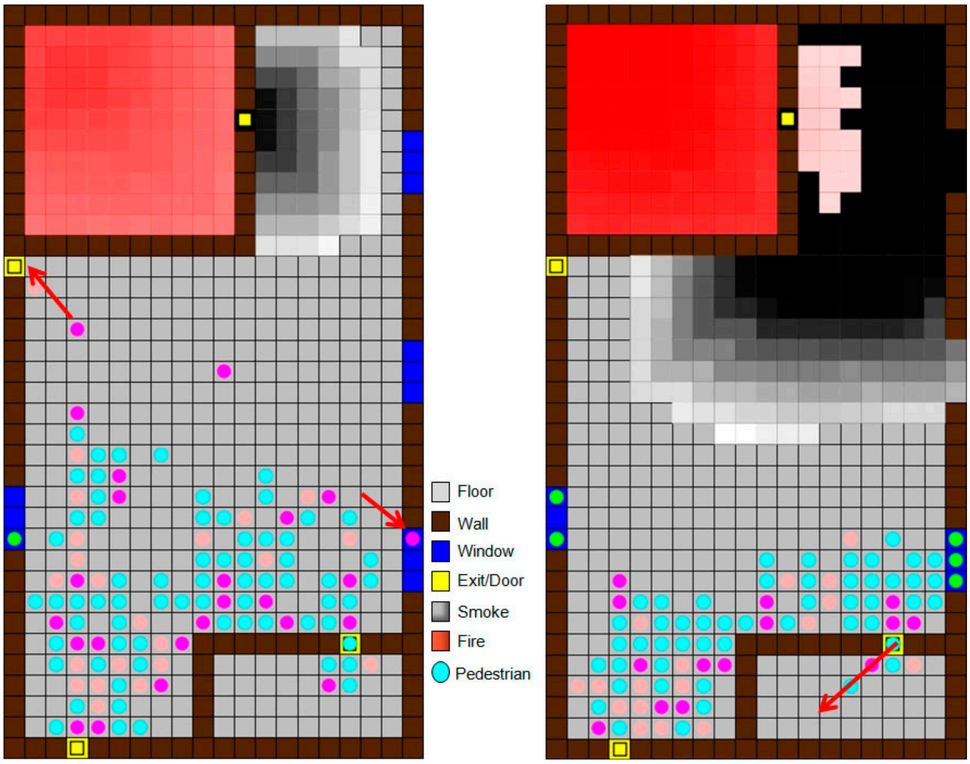


Figure 5-11 Evacuation behaviour after pedestrian agents panic; they search for alternative exits, move toward windows or hide in a room

Figure 5-12 shows the end of an evacuation simulation, in which black smoke and the fire damages all the space in the building. Four causalities (white dots) and seven injuries (green dots) are rescued from this building. A group of victims is found near the main exit, some pedestrian agents are rescued from a room and some are rescued from the windows.

Figure 5-12 The end of an evacuation simulation, showing the location of deaths and injuries who were rescued by fire fighters

These figures, of course, only represent one run of the simulation. Individual movement, evacuation behaviours and the outputs will be different in every run of the simulation. Therefore, analysis of the simulation will be based on a large number of run times in order to provide more statistically significant and reliable results. The sensitivity analysis uses the results of 200 simulation runs by the A* algorithm (A*) and the Priority Queue Flood Fill algorithm (PF), examining egress selection and the number of victims by changing the following parameters. In each test, other parameters are fixed as displayed in Table 6-1.

5.5.1 Degree of Patience

As Section 5.3.1 introduced, degree of patience is designed to simulate pedestrian aggressive behaviour, such as skip the queue or change egress routes. The higher level of patience represents the longer time that pedestrian agents would queue behind another agent and remain the current evacuation route. For example, if a pedestrian agent's level of patience is 10, he stays at the current location for 10 steps if his next step is occupied, and he might change his evacuation route at the 11th step.

In this test, four different ranges of degree of patience were established. Firstly, degree of patience was assigned to 0, therefore all pedestrian agents are impatient and would not remain in the queue. Next, degree of patience was assigned to a range of steps as everyone has a different level of patience. Therefore, three different ranges of steps from 0 to 5, 0 to 10 and 0 to 20 were assigned in test 2, 3 and 4 to identify the influences of changing their maximum waiting steps. At the beginning of each simulation, every pedestrian agent is uniformly assigned to a level of patience.

Table 5-4 shows the results of varying the degree of patience parameter. The longer time that pedestrian agents wait behind the queue led to a safer and faster evacuation, which more people successfully evacuated in a shorter time and less numbers of deaths and injuries occurred. This phenomenon is to be expected because people move in an orderly manner could avoid friction and repulsion of evacuees that cause clogging at an exit.

Table 5-4 The results (median value of 200 runs) for tests of the degree of patience

	A*				PF			
	Test1	Test2	Test3	Test4	Test1	Test2	Test3	Test4
Number of Evacuees at Main Exit	142	149	150	151	139	151	154	157
Evacuation Time at Main Exit	188 sec	176 sec	170 sec	173 sec	191 sec	183 sec	180 sec	173 sec
Number of Evacuees at Emergency Exit	14	16	17	17	14	13	13	14
Evacuation Time at Emergency Exit	73 sec	76 sec	78 sec	79 sec	72 sec	71 sec	71 sec	73 sec
Number of Evacuees at Windows	19	20	19	19	18	16	16	15
Evacuation Time at Windows	136 sec	136 sec	137 sec	134 sec	140 sec	138 sec	138 sec	134 sec
Number of Deaths	11	8	7	6	12	9	8	7
Number of Injuries	32	27	26	26	32	26	24	22
Test1: patience degree 0; Test2: patience degree 0-5; Test3: patience degree 0-10; Test4: patience degree 0-20								

5.5.2 Condition of Passing Door Speed

In addition to the degree of patience, people who slow down their speed to pass through a door influence other people behind them. The passing door rate was designed to test evacuation flow and identify if the delay time influence their evacuation decision and movement. Four different conditions were designed for the sensitivity test.

In test 1, pedestrian agents would not decrease the speed when they encounter a door. In test 2, pedestrian agents decrease a maximum of 0.4 m/s in order to pass through the door. In addition to the condition of test 1, test 3 adds a condition that pedestrian agents slow down their speed at the door if the number of evacuating people exceeds the capacity of the exit, and the model assumes that it only happens when pedestrian agents panic. Test 4 includes the conditions of test 2 and over exit capacity. The concept of capacity is based on an equal usage of exits in the building (Ching and Winkel, 2012), so the calculation of an exit capacity considers the following steps. Firstly, each door is assigned an average usage number by dividing the total number of pedestrian agents by the number of exit agents. For example, if a model simulates 200 occupants in a building with two available exits, ideally, each exit should be used by 100 occupants during the evacuation. Secondly, a door agent detects pedestrian agents and counts the total number of occupants who are heading in that direction. If the number of people who are moving towards an exit exceeds the exit capacity, pedestrian walking speed becomes slower than the defined speed.

Figure 5-13 shows average evacuation time that every pedestrian agent spent at the main exit. A delay time occurred in test 3 and 4 when the panicked crowd piled up at the door after they realised it was a real hazard. Similar trends of evacuation time occurred in the tests of with and without the condition of over exit capacity, especially test 1 and 3 were almost the same. A potential reason was that almost half of the total pedestrian agents evacuated through the main exit before they identified smoke and started panicking, therefore the condition was limited or inactive by the remainders in this scenario.

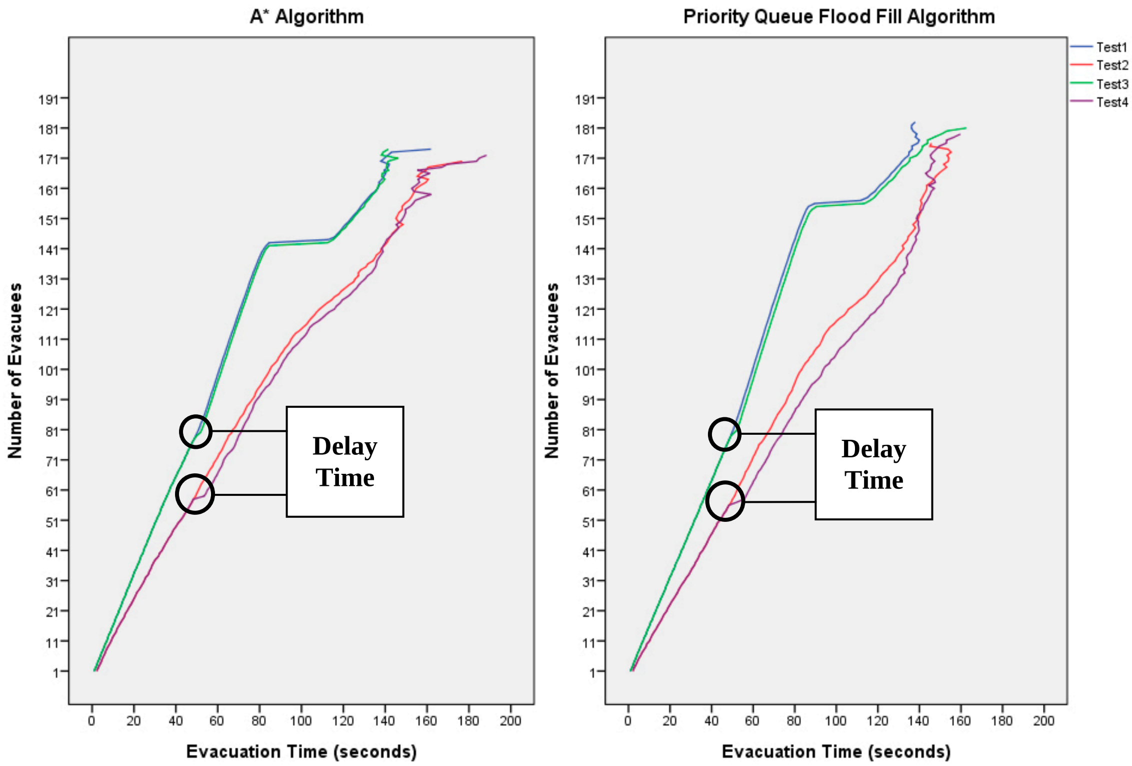


Figure 5-13 Individual evacuation time at the main exit

Table 5-5 shows the results of varying the passing door speed parameter. If pedestrian agents remained the same walking speed at the door, more people evacuated through the main exit (test 1 and 3). In contrast, more people tried alternative egress routes, such as moved to an emergency exit or windows, when they found the delay of evacuation near the main exit (test 2 and 4). The delay time led pedestrian agents to change their behaviour and thus influenced the following events. Although the results of these tests had no/small differences under the condition of over exit capacity, this condition significantly influenced the results of real fire scenarios, such as Rhode Island nightclub fire scenario.

Table 5-5 The results (median value of 200 runs) for tests of the passing door speed

	A*				PF			
	Test1	Test2	Test3	Test4	Test1	Test2	Test3	Test4
Number of Evacuees at Main Exit	162	152	162	150	172	158	171	154
Evacuation Time at Main Exit	142 sec	168 sec	142 sec	170 sec	141 sec	173 sec	142 sec	180 sec
Number of Evacuees at Emergency Exit	14	17	14	17	9	13	10	13
Evacuation Time at Emergency Exit	73 sec	78 sec	73 sec	78 sec	66 sec	71 sec	67 sec	71 sec
Number of Evacuees at Windows	16	18	16	19	12	15	12	16
Evacuation Time at Windows	126 sec	133 sec	127 sec	137 sec	126 sec	135 sec	128 sec	138 sec
Number of Deaths	4	6	4	7	3	6	3	8
Number of Injuries	20	25	20	26	15	22	16	24
Test1: no change; Test2: pedestrian walking speed decrease by 0.4 m/s at the door; Test3: test1 + over exit capacity; Test4: test2 + over exit capacity								

5.5.3 Percentages of Egress Selection

Section 5.4.5 introduced that pedestrian agents change their evacuation movement after they panic. Pedestrian agents are uniformly assigned to a percentage to select one of the four evacuation decisions, including evacuating through the main exit, evacuating through an emergency exit, escaping through windows and hiding inside a room, in terms of the percentage that were designed below. Different percentages were assigned to each evacuation decision in order to simulate evacuation movement. A full sensitivity test should be conducted by assigning regular intervals to each egress selection, but this section only presents four tests that were established based on specific conditions as explained below.

In test 1, the percentage of each selection was assigned to an equally distributed percentage, which pedestrian agents had a possibility of selecting the main exits (25%), emergency exits (25%), windows (25%) or rooms (25%) as their final destination. In test 2, the percentage of each selection was assigned based on the frequency of the related behaviour that occurred in the fire reports. In Figure 4-6, three fire reports mentioned that occupants evacuate through the main exits, 11 reports recorded that occupants jump or wait for rescue at windows, eight reports mentioned that occupants find a place to hide, and four reports described that occupants search for alternative route. Therefore, a percentage of 12% was assigned to the main exits, 15% to emergency exits, 42% to windows and 31% to rooms. Test 3 considered that pedestrian agents mainly evacuate through exits (with 40%, respectively) rather than jumping from windows or hiding in rooms (with 10%, respectively). Finally, main exits were considered the most popular evacuation route in most of the fire incidents. Therefore, the percentages in test 4 were changed to main exit (50%), emergency exit (30%), windows (10%) and rooms (10%).

Table 5-6 shows the results of varying the percentages of egress selection. Overall, the numbers of deaths and injuries (excluding those who were counted at windows) remain a similar value in every test. The differences occurred in the numbers of evacuees at different egress routes, showing that the higher percentage that was assigned to exits or windows the more number of evacuees simulated. When the percentage of main exit reached 50% (test 4), over 3/4 of total pedestrian agents evacuated through the main exit and no one used windows. The varying percentages for pedestrian agents hiding in a room had no significant differences in these tests. However, it is difficult to identify if the model that uses specific percentages simulates accurate results in this virtual environment. Therefore, the percentages are adjusted when the model is applied to real data (Section 6.2).

Table 5-6 The results (median value of 200 runs) for tests of the egress selection

	A*				PF			
	Test1	Test2	Test3	Test4	Test1	Test2	Test3	Test4
Number of Evacuees at Main Exit	145	136	148	156	152	142	154	157
Evacuation Time at Main Exit	173 sec	168 sec	168 sec	181 sec	174 sec	168 sec	179 sec	190 sec
Number of Evacuees at Emergency Exit	16	9	26	27	13	9	20	19
Evacuation Time at Emergency Exit	77 sec	68 sec	76 sec	97 sec	71 sec	66 sec	83 sec	80 sec
Number of Evacuees at Windows	25	41	12	0	20	36	10	0
Evacuation Time at Windows	145 sec	155 sec	122 sec	N/A	145 sec	157 sec	126 sec	N/A
Number of Deaths	8	8	6	9	7	7	8	12
Number of Injuries	32	48	19	9	28	42	19	11
Number of Deaths in Room	1	1	1	1	1	1	0	1
Test1: main exit (25%), emergency exit (25%), windows (25%) and room (25%); Test2: main exit (12%), emergency exit (15%), windows (42%) and room (31%); Test3: main exit (40%), emergency exit (40%), windows (10%) and room (10%); Test4: main exit (50%), emergency exit (30%), windows (10%) and room (10%)								

5.5.4 Possibility of Being Rescued

As Section 5.4.6 described, pedestrian agents were designed either die or be rescued after they fainted in the building. Those who fainted are uniformly assigned to a percentage in order to identify if they will be rescued by fire fighters, and they are counted as injuries once they were rescued. This section displays the sensitivity test on the percentages of rescue possibility, testing from 0 to 100 of rescue percentages. In the results, the number of injuries includes the number of pedestrian agents who were rescued after they fainted and the number of evacuees who were rescued from windows. The rescue percentage only influences the pedestrian agents who were rescued after they fainted.

Table 5-7 shows the results of varying the percentages of rescue possibility. According to the results, the number of evacuees and evacuation time at each egress route remain the same over the tests. If the model designed all pedestrian agents who fainted die in the scene, a total number of 14 deaths (A*) and 0 injuries (excluding the 19 people who were rescued from windows) occurred in the scenario. The number of injuries gradually increased from 0 to 15 (A*) until the percentage of rescue possibility reached 100%. The same trend, which the number of deaths gradually decreased and the number of injuries gradually increased, displayed in the model when using the Priority Queue Flood Fill algorithm.

Table 5-7 The results (median value of 200 runs) for tests of the rescue percentage

	A* Algorithm (A*)										
	0	10	20	30	40	50	60	70	80	90	100
Number of Evacuees at Main Exit	150	150	150	150	150	150	150	150	150	150	150
Evacuation Time at Main Exit	170 sec	170 sec	170 sec	170 sec	170 sec	170 sec	170 sec	170 sec	170 sec	170 sec	170 sec
Number of Evacuees at Emergency Exit	17	17	17	17	17	17	17	17	17	17	17
Evacuation Time at Emergency Exit	78 sec	78 sec	78 sec	78 sec	78 sec	78 sec	78 sec	78 sec	78 sec	78 sec	78 sec
Number of Evacuees at Windows	19	19	19	19	19	19	19	19	19	19	19
Evacuation Time at Windows	137 sec	137 sec	137 sec	137 sec	137 sec	137 sec	137 sec	137 sec	137 sec	137 sec	137 sec
Number of Deaths	14	13	12	10	9	7	6	4	3	1	0
Number of Injuries*	19	21	22	24	25	26	28	29	31	32	34
	Priority Queue Flood Fill Algorithm (PF)										
Number of Evacuees at Main Exit	154	154	154	154	154	154	154	154	154	154	154
Evacuation Time at Main Exit	180 sec	180 sec	180 sec	180 sec	180 sec	180 sec	180 sec	180 sec	180 sec	180 sec	180 sec
Number of Evacuees at Emergency Exit	13	13	13	13	13	13	13	13	13	13	13
Evacuation Time at Emergency Exit	71 sec	71 sec	71 sec	71 sec	71 sec	71 sec	71 sec	71 sec	71 sec	71 sec	71 sec
Number of Evacuees at Windows	16	16	16	16	16	16	16	16	16	16	16
Evacuation Time at Windows	138 sec	138 sec	138 sec	138 sec	138 sec	138 sec	138 sec	138 sec	138 sec	138 sec	138 sec
Number of Deaths	16	14	12	11	9	8	6	5	3	1	0
Number of Injuries*	16	17	19	21	23	24	26	28	30	31	33
*Number of injuries include the number of pedestrian agents who were rescued from windows and the number of pedestrian agents who were rescued after they fainted in the building											

5.6 Chapter Summary

This chapter introduced the development of evacuation behaviour and phenomena for agent-based models. Three types of agents (pedestrian, door and fire/smoke) and their interactions were developed (Figure 5-2) to simulate general evacuation situations that are suitable for any fire disaster. A number of parameters were tested to ensure the model simulates expected evacuation behaviour and results. Although the model performs expected evacuation movement and is not overly sensitive to any of the parameters, the final outputs should be compared to statistics from actual fire disasters in order to validate the realism and accuracy of the evacuation model. The next chapter introduces the specific parameters, navigation algorithms and fire incidents used in the model before applying to real data.

6. Model Implementation

Introduction and Background	Contents of Evacuation Modelling	Developing Research Questions	Developing an Evacuation Model	Simulation Outcomes	Discussion	Conclusion and Further Work
Ch. 1	Ch. 2	Ch. 3	Ch. 4, 5 and 6	Ch. 7, 8 and 9	Ch. 10	Ch. 11

6.1 Introduction

A number of human behavioural and condition action rules were developed for the generic agent-based evacuation model (Section 4.4, 5.3 and 5.4). The designed agents and rules are relevant for a general evacuation simulation and can be designed using various programming languages and toolkits. As a first step towards identifying a suitable software package for this research, existing implementations and reviews were examined (Nikolai and Madey, 2009; Allan, 2009; Robertson, 2005a; Castle *et al*., 2005; Serenko and Detlor, 2002). One of the toolkits, the Repast (Recursive Porous Agent Simulation Toolkit), using Java programming, is selected to help developing multi-agent behaviour, complex interactions and navigation algorithms in this thesis. More details and the advantages of using Repast are given in Appendix C.

Based on the results of sensitivity analysis (Section 5.5) and preliminary tests (Section 7.2), final parameter values are displayed in this chapter. In addition, the modification and implementation of the selected navigation algorithms are proposed to address the limitations of the standard calculation (Section 2.6.4). Finally, three real fire incidents that are applied to the model are introduced before displaying the results of the calibration, evaluation and validation in the next few chapters.

6.2 Parameters Used in the Evacuation Model

As noted in Section 3.3.1, this thesis designs two different grid sizes (0.5 m^2 and 0.3 m^2). In grid-based models, one person is generally restricted to one grid, which the size of the grid was developed in terms of the average human body size (Section 2.4). One grid size (0.5 m $\times$ 0.5 m) was defined as the general human shoulder to shoulder size, and another grid size (0.3 m $\times$ 0.3 m) was created based on the depth of a human body. The smaller grid size increases the number of people standing from four to 11 per square metre, and thus it can simulate a situation with high pedestrian density. However, the decrease in the grid size might increase the pedestrian flow when people are passing through a door. For example, a 1m door with two 0.5 m^2 grids would increase to three 0.3 m^2 grids, meaning an additional person could pass through the door at the same time.

To understand the influence of different grid sizes on simulation results and to identify a suitable grid size for evacuation models, the simulation outcomes are compared in Section 9.2. In addition to grid size, the thesis proposed that two selected navigation algorithms, A* algorithm and Priority Queue Flood Fill algorithm, should be modified in the model in order to simulate flexible evacuation dynamics (Section 2.6.4). The details of modifying navigation algorithms are introduced in Section 6.3.

Once the generic model is developed, all the parameters that were established in the model are fixed. These parameters were designed based on empirical data or previous research if applicable. Otherwise, a sensitivity analysis was conducted to identify how simulation was influenced by varying the parameters (Section 5.5). Based on the sensitivity tests, the model is further applied to the real data in order to simulate similar results to fire report statistics (Section 7.2). According to the findings from the preliminary model, the calibration involves adjustments of parameters and a number of issues fixed (Section 7.3.1). Table 6-1 displays the final parameters that are determined for the 0.5 m^2 grid-based evacuation model. The parameters in relation to grid size are changed in the 0.3 m^2 grid-based model, including pedestrian walking speed and fire/smoke spreading speed.

Table 6-1 All parameters that are designed for the 0.5 m^2 grid-based evacuation model

Parameter	Value	Definition	Reference
Unit of time	1 tick	0.04 seconds	N/A
Distribution of pedestrian agents in space	Random distribution	The model randomly places pedestrian agents in space	N/A
Age	5 - 90 years old	Each pedestrian agents is assigned an age from 5 to 90 years old (with an assumption of normal walking capability)	N/A
Pedestrian walking speed	Children: 11 ticks/grid Elderly: 12 ticks/grid Adult: 10 ticks/grid	1.08 m/s 1.04 m/s 1.27 m/s	(Yeo and He, 2009)
Fast walking speed	Pedestrian walking speed — 0-5 ticks	Pedestrian agents increase walking speed to a maximum of 2.5 m/s when they start panic	Based on the highest reported speed (Willis *et al.*, 2004)
Slow walking speed	Pedestrian walking speed + 0-5 ticks	Pedestrian agents decrease walking speed to about 60% of the normal walking speed if they inhale smoke	Based on the speed of crawlers (Nagai *et al.*, 2006)
Passing door speed	Pedestrian walking speed + 0-5 ticks	Pedestrian agents decrease walking speed by 0.4 m/s when an exit exceeds exit capacity	Sensitivity analysis
Degree of patience	0-10 decision steps	Pedestrian waits a maximum 10 steps before changing the original decision	Sensitivity analysis
Inhale smoke time	Accumulated value of inhaling smoke time (+1 tick)	Inhale time gradually increases when a pedestrian agent contacts a fire agent	N/A
Carbon monoxide tolerance level	Maximum 15000 ticks	Pedestrian faint within 10 minutes if inhale smoke	(Goldstein, 2008)
Type of door	Main exit; Emergency exit; Room; Unavailable	Pre-defined the type of door	Pre-defined layout in terms of a fire report
Number of evacuees	Accumulated value of evacuees	+1 person when a pedestrian agent pass through the exit	N/A
Fire/smoke spreading speed	35-66 ticks	0.19 m/s to 0.35 m/s	(Yu and Zhang, 2009)
Time that the door delays the spread of fire and smoke	750 ticks	A door agent will stop fire agents spreading out of the door for 30 seconds	(U.S. Fire Administration, 2011)
Percentages of the evacuation decisions	Main exit 40% Emergency exit 20% Window 15% Hide 15% Stay 10%	The probability of evacuation decisions uses a uniformly distributed random variable	Sensitivity analysis
Percentage of fainted people will be rescued	50%	Pedestrian agents who fainted have 50% possibility to be rescued by fire fighters	Sensitivity analysis

Before applying the model to a specific scenario, some parameters from the real data is required to input into the model. For example, the building layout from a fire disaster, the number of attendants occurred in the building and the origin of fire.

Firstly, a fire case is selected to become the evacuation scenario for the model from one of three building scenarios: the Gothenburg dance hall, the Rhode Island nightclub and the Hamlet chicken processing plant (Section 6.4). Based on the selected fire case, the number of pedestrian agents is assigned as the estimated number of attendants that were recorded in the fire reports. Next, the location of the fire is generated to a geo-location on the grid-based environment. The parameters for these scenarios are set up as shown in Table 6-2.

Table 6-2 Scenario parameters in three fire cases

Fire Case	Number of Pedestrian Agents	Fire Location
Gothenburg dance hall	400	Southeast stairwells
Rhode Island nightclub	458 (500 in the preliminary model)	Platform
Hamlet chicken processing plant	90	Processing room

After the scenario of a fire disaster is set up, further modelling parameters are decided in terms of a navigation algorithm and a grid size. To simulate pedestrian movement, a navigation algorithm is selected from the modified A* algorithm (Section 6.3.1) or the modified Priority Queue Flood Fill algorithm (Section 6.3.2) to calculate pedestrian egress selection on a 0.5 m^2 or 0.3 m^2 grid-based space.

In addition to the parameters that are required to input into the model, other factors and parameters that were established for the three types of agent (pedestrian, door and fire/smoke) remain the same while simulating any of the fire scenarios. Furthermore, all the parameters are fixed during the multiple simulation runs of a scenario in order to produce more statistically significant and reliable results. The number of runs for each scenario is determined in Section 7.3.2.

6.3 Modifying the Navigation Algorithms

The A* algorithm from the shortest path search approach and the Priority Queue Flood Fill algorithm from the potential field approach were selected to become the representative navigation algorithms of the evacuation model in this thesis (Section 2.6.4). To use these two navigation algorithms, which identify a route based on a start point and an end point, the model assumes pedestrian agents know the location of their destinations in the space. The limitations of the current calculation were identified in

Section 2.6.4, and a solution was proposed comprising additional calculation steps and available directions of movement while calculating the cost on each grid (Figure 6-1). The following sub-sections introduce the modification process by comparing the full calculation steps of the standard A* algorithm and Priority Queue Flood Fill algorithm.

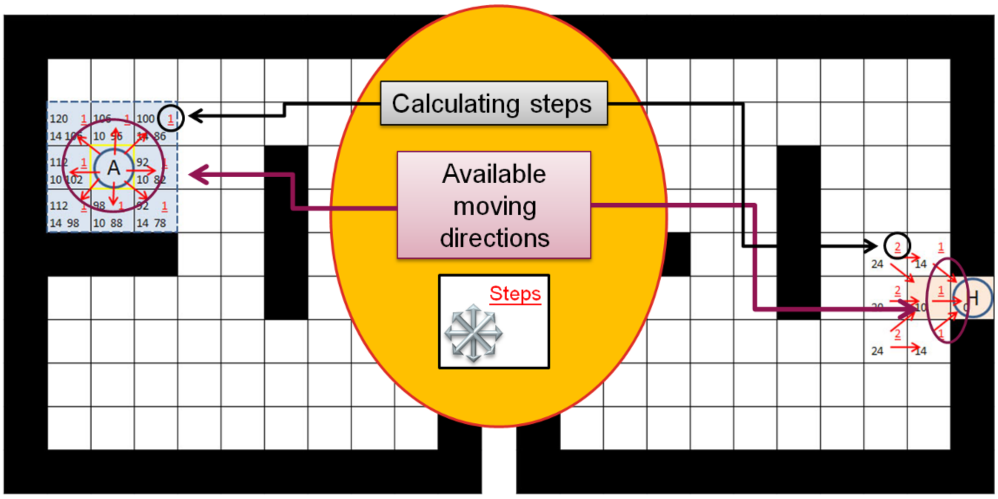


Figure 6-1 Modified A* algorithm (left) and priority queue algorithm (right) with additional calculation steps and available directions of movement

6.3.1 Modified A* Algorithm

Section 2.6.1 explained how the standard A* algorithm calculates a route from an individual starting location to a final destination. This section explains the modification by comparing the full calculation steps of the standard A* algorithm as displayed from Figure 6-2 to Figure 6-7. The modified A* algorithm adds a calculation step number to each cell when calculating step by step (Figure 6-2).

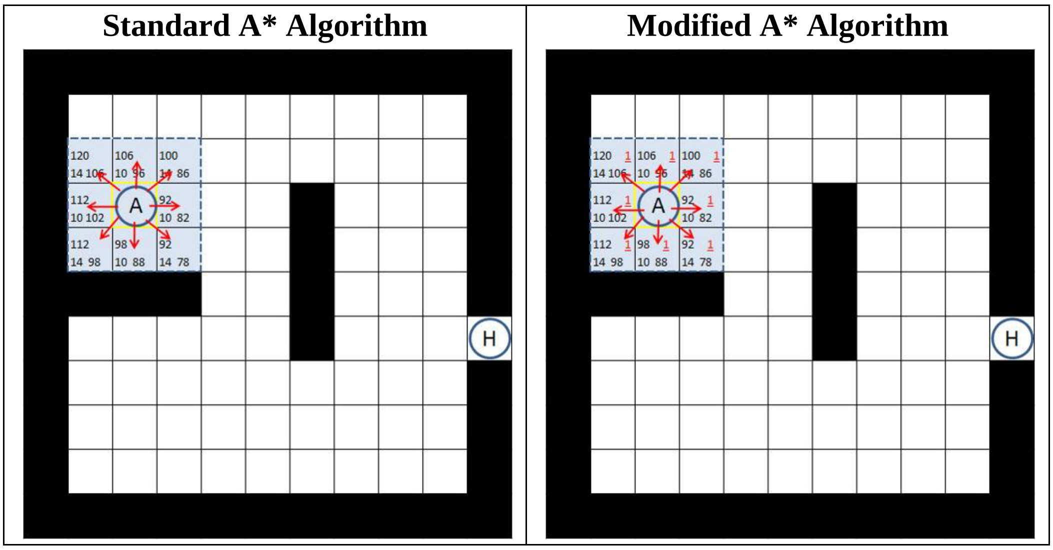


Figure 6-2 A comparison of the standard A* algorithm and the modified A* algorithm: both algorithms calculate the eight neighbouring cells around the starting point, and the modified A* algorithms adds calculation step numbers (the red underlined number) to each grid

Next, the algorithm visits all cells that have the lowest score ('f') of distance ('g')-plus-cost ('h') rather than only the cell with the lowest 'h' value, which is recognised as the closest cell to the final target. For example, Figure 6-3 shows the standard A* algorithm only visits one cell, which has the lowest distance-plus-cost score (92) and the lowest 'h' value (78), and identifies three open cells from the neighbours of the selected cell, whereas the modified A* algorithm visits two cells that have the same lowest 'f' scores (92) on calculation step 1 and identifies four open cells that are adjacent to the two selected cells.

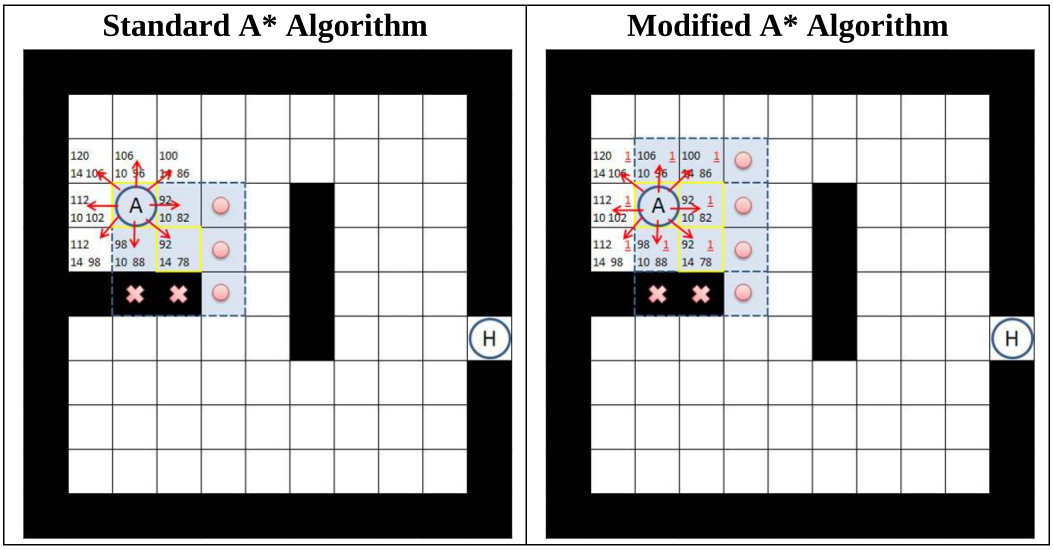


Figure 6-3 A comparison of the standard A* algorithm and the modified A* algorithm: The standard A* algorithm selects the cell which contains the lowest distance-plus-cost score as well as the lowest h value that represents the shortest distance to the final target. The modified A* algorithm visits all the cells that contain the same lowest distance-plus-cost score. Following that, the algorithm identifies whether the adjacent cells are open or closed cells (yellow frames represent visited cells)

Following that, the algorithm calculates the distance-plus-cost values of the open cells that were previously identified and then determines the next cells to visit. Figure 6-4 displays the values of three cells that were calculated by the standard A* algorithm and the cell that has the lowest 'f' score (92) and the lowest 'h' value (64) are selected to be visited; the modified A* algorithm calculates four cells and adds calculation step 2 to these cells.

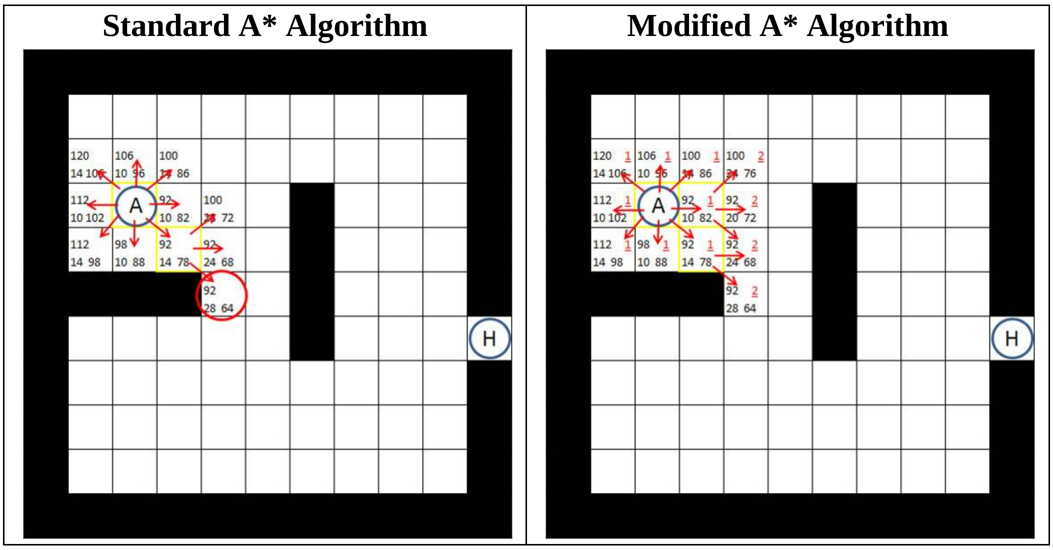


Figure 6-4 A comparison of the standard A* algorithm and the modified A* algorithm: The standard A* algorithm calculates the distance values of the neighbour cells around the selected cell. The modified A* algorithm calculates the neighbours of the two selected cells to calculation step 1

Both algorithms continue their calculations and identify the next cells to be visited based on their selection regulation until the lowest distance-plus-cost values in the space are all visited. Once this happens, the standard A* algorithm selects a cell that has the secondary lowest-plus-distance score and the lowest 'h' score, and the modified A* algorithm selects all cells that contain the same secondary lowest-plus-distance scores in the space. In Figure 6-5, the standard A* algorithm selects a cell that has the 'f' score (98) and the lowest 'h' value (60) to become the next cell to be visited, and the modified A* algorithm selects all cells that contain the 'f' score (98), including one cell at calculation step 1 and another on calculation step 3.

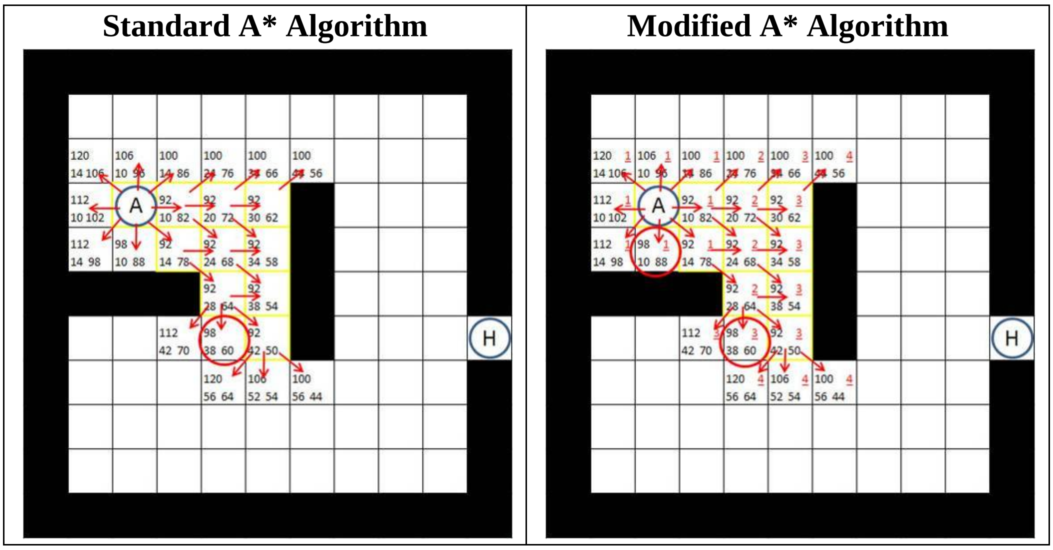


Figure 6-5 A comparison of the standard A* algorithm and the modified A* algorithm: if the A* algorithm has visited all the cells with the lowest distance-plus-cost score (92), it starts to visit those with the secondary lowest distance-plus-cost score (98). The standard A* algorithm visits the lowest 'f' score and 'h' value, and the modified A* algorithm selects all cells with the same lowest 'f' scores

As mentioned in Section 2.6.1, the configuration was developed to demonstrate how, using the calculation, occupants avoid obstacles (walls) whilst moving towards an exit. As Figure 6-6 displays, the standard A* algorithm visits cells mainly at the south side of the wall, whereas the modified A* algorithm visits cells at the south and north sides of the wall, so pedestrian agents can move in two directions to avoid the wall.

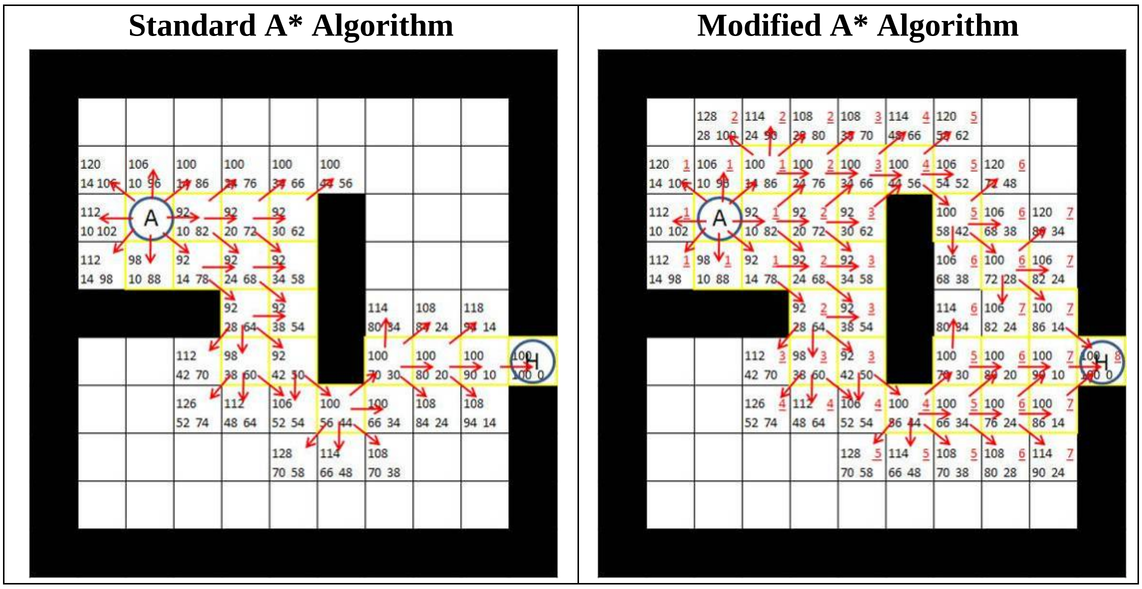


Figure 6-6 A comparison of the standard A* algorithm and the modified A* algorithm: the standard A* algorithm visits cells at the south side of the wall, and the modified A* algorithm visits cells at the north and south sides of the wall

Finally, the standard A* algorithm identifies a path from the final target to the starting point by following the visited cells with the available directions of movement, and the modified A* algorithm identifies a path by following the available directions of movement with the gradually decreasing numbers of calculation steps on the visited cells from the final target and to the starting point. For example, multiple paths were identified from final target H (calculation step 8) to the starting point A (calculation step 0) by the modified A* algorithm (Figure 6-7).

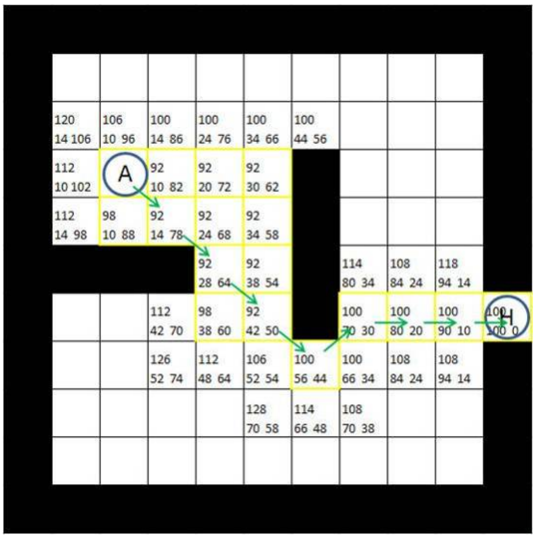
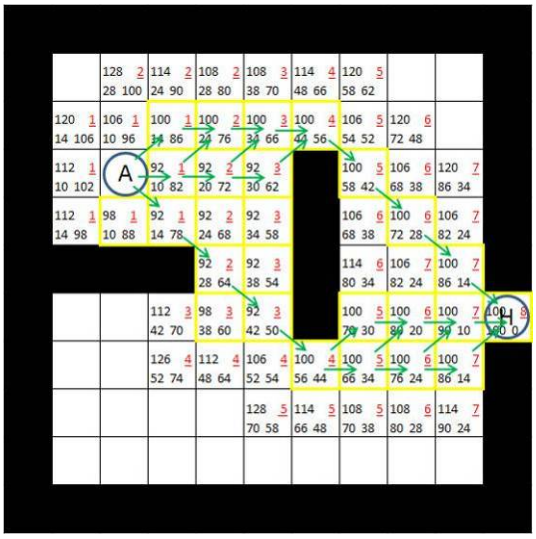
Standard A* Algorithm	Modified A* Algorithm
	

Figure 6-7 A comparison of the standard A* algorithm and the modified A* algorithm: a path is identified from the final target to the starting point. The standard A* algorithm searches through the visited cells by following the available directions of movement. The modified A* algorithm identifies a path using the number of calculation steps and available directions of movement for the visited cells

According to the final results of the standard and modified A* algorithms in Figure 6-7, the standard A* algorithm identified one single route, whereas the modified A* algorithm identified eight different potential paths (Figure 6-8). In addition, these eight potential routes comprised the same distance (five diagonal and three horizontal grid-movements) and number of cells (8), the same as the route in the standard A* algorithm. Therefore, the method of using the additional number of calculation steps and directions in the A* algorithm increases the possibility of route selections.

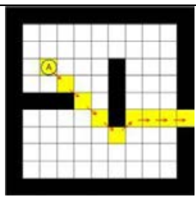
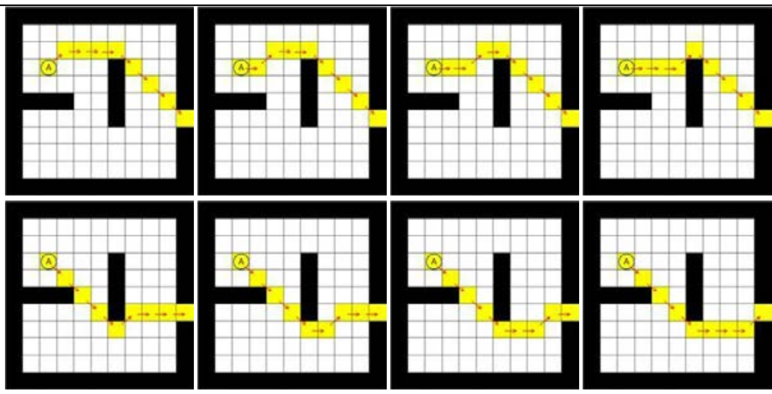
A* Algorithm	Potential Routes
Original	
Modified	

Figure 6-8 The potential paths that were calculated by the standard and modified A* algorithms

6.3.2 Modified Priority Queue Flood Fill Algorithm

Section 2.6.2 introduced the calculation of the Priority Queue Flood Fill algorithm, which uses a "potential table" to store all the distance costs to represent the distance from each grid to the final target. This section explains the modification by comparing the full calculation steps of the standard Priority Queue Flood Fill algorithm and the modified Priority Queue Flood Fill algorithm, as displayed from Figure 6-9 to Figure 6-13. Overall, the calculation method of the modified Priority Queue Flood Fill algorithm remain mostly the same as the original calculation, but adds a number of calculation steps and available directions from every cell. The calculation of the modified Priority Queue Flood Fill algorithm starts from the final destination and calculates values of the eight neighbours around the visited cell (Figure 6-9).

Standard Priority Queue Flood Fill Algorithm	**Modified Priority Queue Flood Fill Algorithm**

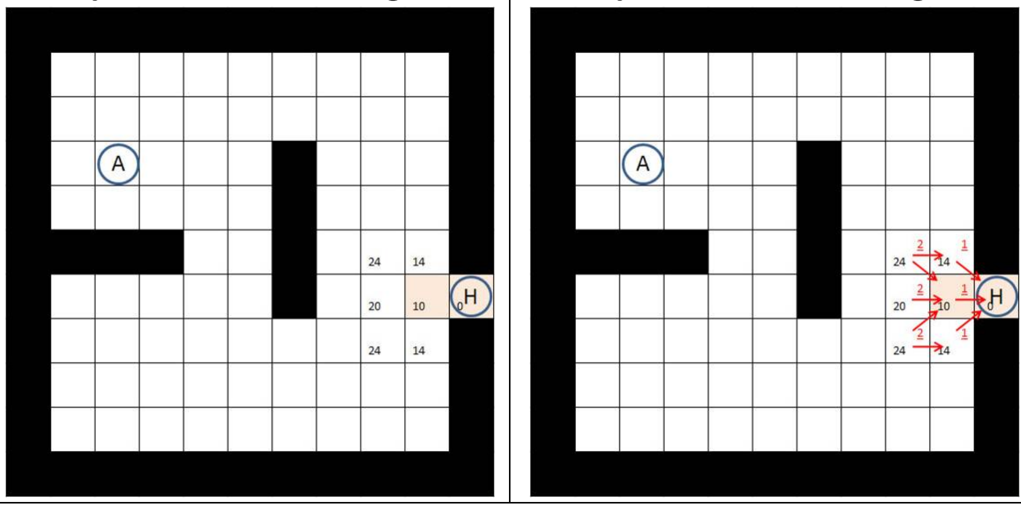


Figure 6-9 A comparison of the standard Priority Queue Flood Fill algorithm and the modified Priority Queue Flood Fill algorithm: both algorithms calculate the distance of adjacent cells at the final target and select the lowest distance cost to be the next visited node (the cells in light pink colour represent visited cells). Calculation steps and available directions of movement are added in the modified Priority Queue Flood Fill algorithm

Both algorithms set the lowest distance costs as priority nodes and calculate their adjacent cells. Following that, both algorithms visit a cell and calculate distance costs by putting the lowest distance cost in the queue and calculating its adjacent cells in terms of their priorities. Figure 6-10 and Figure 6-11 show the distance values for each cell are the same in the standard and modified Priority Queue Flood Fill algorithms.

Standard Priority Queue Flood Fill Algorithm	Modified Priority Queue Flood Fill Algorithm

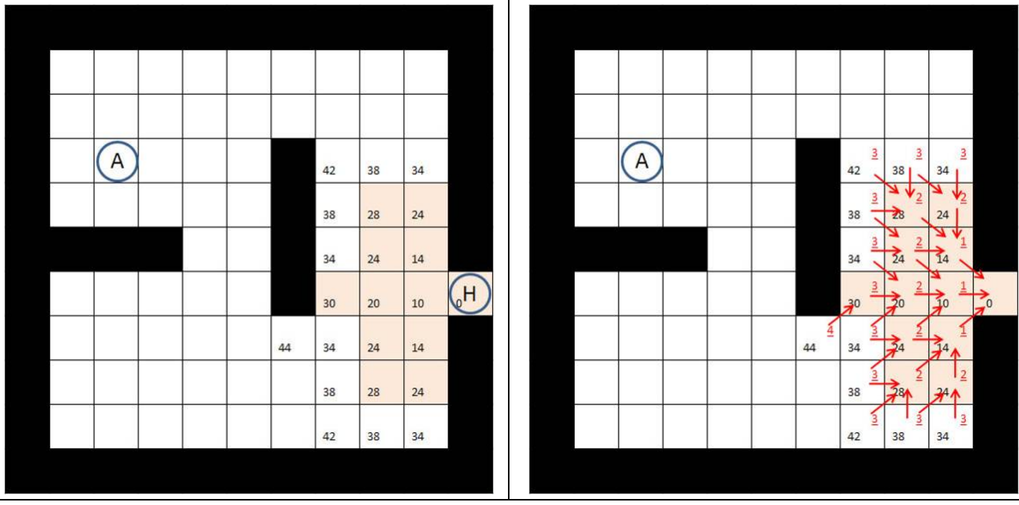


Figure 6-10 A comparison of the standard Priority Queue Flood Fill algorithm and the modified Priority Queue Flood Fill algorithm: both algorithms set the lower distance costs as priority nodes and calculate their adjacent cells

Standard Priority Queue Flood Fill Algorithm	Modified Priority Queue Flood Fill Algorithm

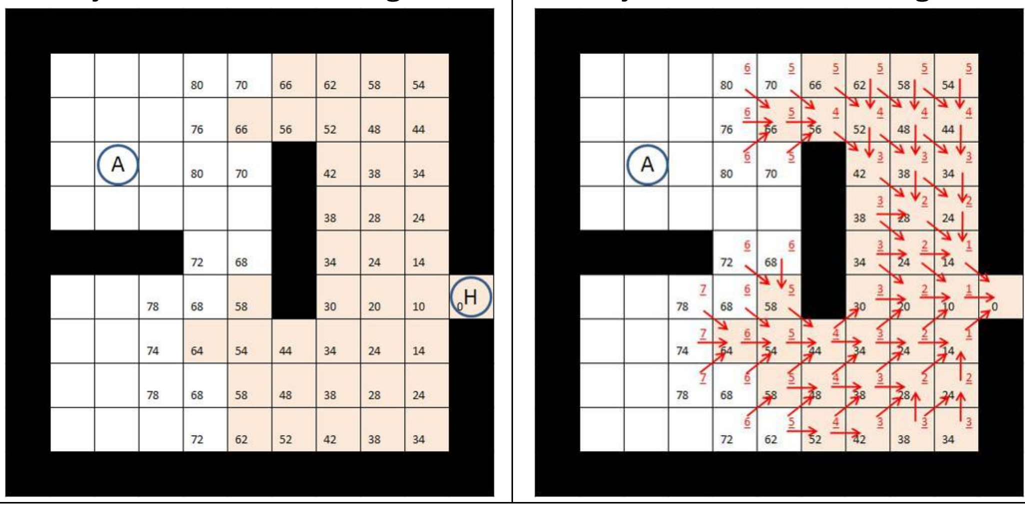


Figure 6-11 A comparison of the standard Priority Queue Flood Fill algorithm and the modified Priority Queue Flood Fill algorithm: both algorithms continue the same loop of calculation: put the lowest distance cost in the queue and calculate its neighbours in terms of their priorities

The calculation ends when all the cells are visited and each cell contains the lowest distance cost. Figure 6-12 shows the final distance values that were calculated by the standard and the modified Priority Queue Flood Fill algorithms. The modified method included an additional number of calculation steps and available directions of movement for each visited cell.

Standard Priority Queue Flood Fill Algorithm	**Modified Priority Queue Flood Fill Algorithm**

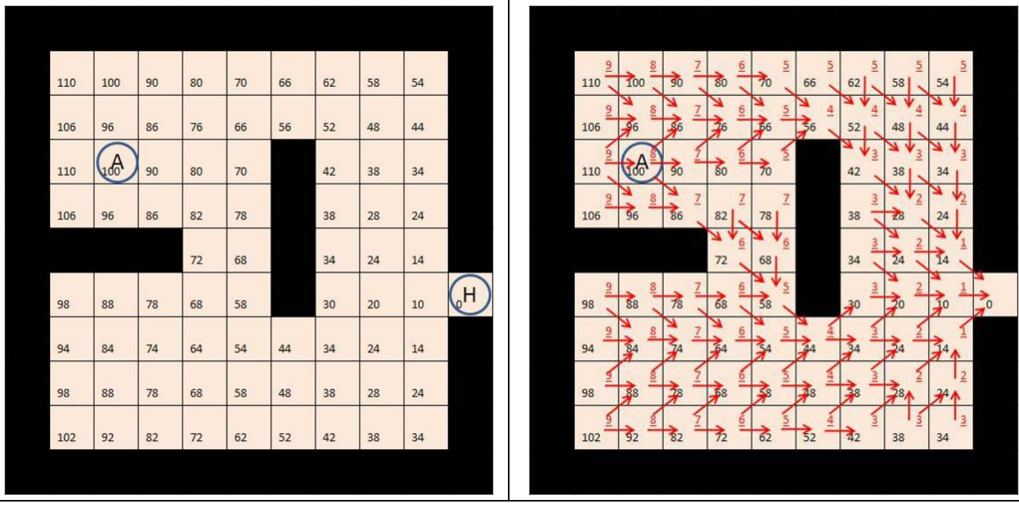


Figure 6-12 A comparison of the standard Priority Queue Flood Fill algorithm and the modified Priority Queue Flood Fill algorithm: the final results of the original and the modified Priority Queue Flood Fill algorithms

After all the lowest distance costs of the cells are identified, a potential map is created to show the distance between a final destination and every cell in the space. The standard Priority Queue Flood Fill algorithm identifies a path from a starting location to the final target by moving to the adjacent cell with the lowest value. For example, the lowest distance value adjacent to starting point A is 86 in Figure 6-13, so a pedestrian agent moves to one of the cells with a value of 86 and then continues by moving to the next cell with the lowest distance cost around the standing cell until the final target is reached.

The modified Priority Queue Flood Fill algorithm identifies a path by following the available directions of movement with gradually decreasing numbers of calculation steps for the visited cells from the starting point to the final target. For example, a pedestrian agent stays on calculation step 8 and follows one of the three available directions to the next cell, which has a number lower than the current calculation step (Figure 6-13). According to the first step of path identification, the modified calculation identifies three potential next cells around starting point A rather than the two recognised by the standard algorithm.

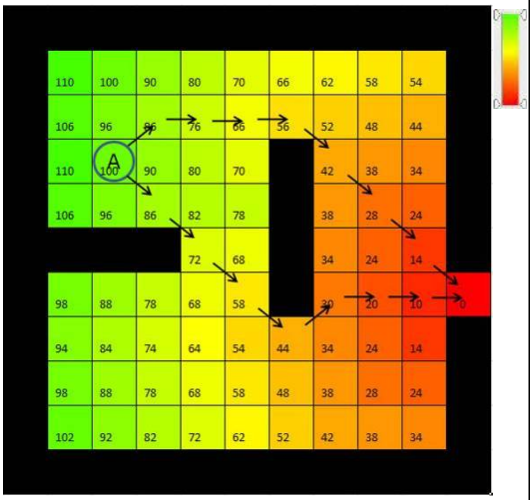
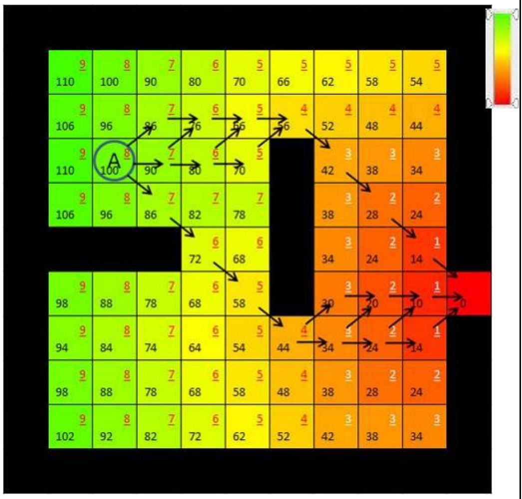
Standard Priority Queue Flood Fill Algorithm	Modified Priority Queue Flood Fill Algorithm
	

Figure 6-13 A comparison of the standard Priority Queue Flood Fill algorithm and the modified Priority Queue Flood Fill algorithm: Coloured potential maps in terms of the distance costs (red represents the cells which are closest to the exit, green represents those which are far from the exit). The routes are identified in terms of the lowest values around the pedestrian standing cell in the standard calculation, and the modified calculation identifies routes according to the calculation steps and available directions of movement

At the end of the identification, a total of eight paths instead of two paths are identified. Figure 6-14 shows the results of the standard and the modified Priority Queue Flood Fill algorithms. In this configuration, the standard Priority Queue Flood Fill algorithm calculated two cells around starting point A had the same lowest values (86) and then produced two potential routes at the end of the calculation. On the other hand, the pedestrian agents selected the number of calculation steps from 8 to 0 while calculating using the modified method. The results show an increase in the possibility of movement from two routes to eight potential routes. These eight potential routes were the same distance (five diagonal and three horizontal grid-movements) and contained the same number of cells (8).

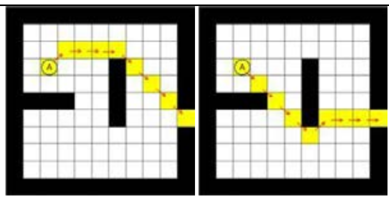
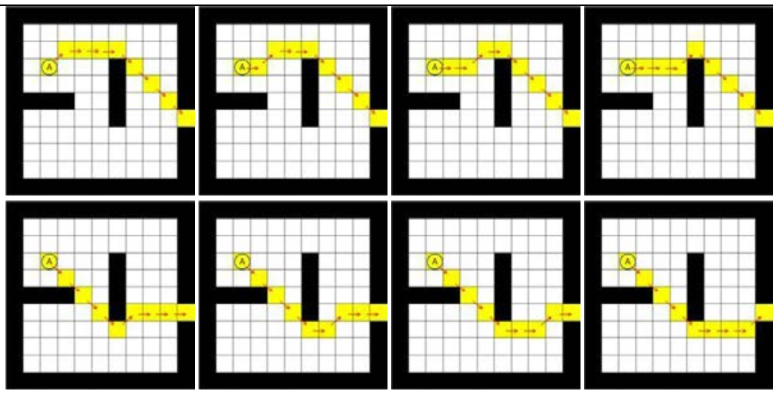
Priority Queue Flood Fill Algorithm	Potential Routes
Original	
Modified	

Figure 6-14 The potential paths that were calculated by the standard and the modified Priority Queue Flood Fill algorithms

6.3.3 Comparisons of the Standard and Modified Navigation Algorithms

After modification, the efficiency, complexity and flexibility of navigation calculation are examined using the same layouts that were displayed in Figure 2-19. Table 6-3 displays the results of the standard and modified algorithms. The increase of an individual's potential routes in a space shows that a pedestrian agent would not always follow the same route in different simulation runs, which represents that occupants in real life would not have the same trajectory toward a destination in an environment.

On one hand, the number of visited cells and the number of calculation steps of the modified Priority Queue Flood Fill algorithm remain the same as the standard calculation. On the other hand, the number of visited cells and calculation steps are about 1.5-2.7 times more than the standard calculation when using the A* algorithm. The differences might increase the system calculation time in the model, therefore this thesis displays the results of system run time for the evacuation simulation to identify which of the algorithms calculates more efficient (Section 8.2.5).

Table 6-3 Results of the standard and modified algorithms in different layouts

Algorithms / Layout and Results	A* Algorithm		Priority Queue Flood Fill Algorithm	
	Modified	Standard	Modified	Standard
Layout 1: empty room (11×11 cells)				
Number of Visited Cells	24	9	82	82
Number of Calculation Steps	117	55	275	275
Number of Potential Routes	56	1	56	1
Layout 2: simple room with obstacles (11×11 cells)				
Number of Visited Cells	27	17	75	75
Number of Calculation Steps	118	74	227	227
Number of Potential Routes	8	1	8	2
Layout 3: two empty rooms (21×11 cells)				
Number of Visited Cells	76	50	164	164
Number of Calculation Steps	322	219	553	553
Number of Potential Routes	6720	1	6720	1
Layout 4: two rooms with obstacles (21×11 cells)				
Number of Visited Cells	78	50	157	157
Number of Calculation Steps	304	193	505	505
Number of Potential Routes	960	1	960	2
Layout 5: complex room (21×11 cells)				
Number of Visited Cells	62	26	151	151
Number of Calculation Steps	256	131	464	464
Number of Potential Routes	375	1	375	1

6.4 Case Studies

To validate the representation of fire disasters in simulations, the model was programmed to recreate actual fire cases that were selected from the studied fire investigation reports (Section 4.2.1). The process of selection is explained as follows. Fire disasters occur in various types of building, such as residential, commercial, educational, industrial, transit stations and others. Of the twenty studied fire investigation reports (see Table 4-1), 11 cases occurred in commercial buildings, seven in residential buildings, one was an industrial disaster, and one happened in a transit station. According to the statistics, fire disasters occur most frequently in commercial buildings such as banks, hotels, nightclubs, office buildings, restaurants and retail stores. More specifically, more deaths and injuries occur in nightclubs than in other fire venues. Therefore, three nightclubs were preliminarily selected before a further decision was made: the Gothenburg dance hall fire (Comeau and Duval, 2000), the Beverly Hill Supper Club fire (Best and Swartz, 1978), and the Rhode Island nightclub fire (Grosshandler *et al.*, 2005).

The fire disasters in these nightclubs had common factors: (1) a large number of attendants (more than 400 people) were inside the building during the fire; (2) the number of victims exceeded 60 people; (3) occupants were mainly evacuating from a single floor; (4) over 50% of the selected behaviour (see Section 4.4) occurred in the fire disasters; (5) the buildings contained secluded rooms and emergency exits; (6) deaths mainly occurred around the exit.

Although the above common factors show most of the behaviours that were identified in Section 4.4, the Beverly Hill Supper Club fire case was excluded due to its complex configuration, no windows, and the fact the evacuation behaviour mainly occurred in one large room, when the distribution of people was spread over nine secluded areas in the building. In addition, the amount of information available for the Gothenburg dance hall fire and the Rhode Island nightclub fire provided greater evidence of human behaviour for the incidents' timelines; this was gathered by the fire fighters or video footage recorded by inside/outside camera operators.

Therefore, the Gothenburg dance hall was the first incident to be developed because the building layout was square and simple (Figure 6-16), and thus it was easy to replicate in the model. Next, the Rhode Island nightclub, including a complex configuration with an additional six rooms and two exits (Figure 6-18), was established to validate human behaviour and evacuation phenomena in the model. Besides these two nightclubs, a third building was selected to establish if this evacuation model is suitable for a different type of building. In order to restrict human evacuation to a single floor, in which pedestrian behaviour on stairs was not taken into consideration, a third building with solely a single floor environment was selected. Of the rest of the studied fire investigation reports, the Hamlet chicken processing plant contained the common building elements defined above, including a single floor, secluded rooms and emergency exits.

The following sub-sections introduce the background to and overview information from the three fire incidents. The first scenario of the nightclub was selected to become the basis of the model development, and the model was validated using another nightclub. Finally, the third scenario was created in order to validate human behaviour in a different type of building.

6.4.1 Dance Hall Fire, Gothenburg, Sweden, 28 October 1998 (Comeau and Duval, 2000)

The Gothenburg dance hall fire occurred in a nightclub on the evening of 28 October 1998 in Gothenburg, Sweden. This fire disaster was investigated by the National Fire Protection Association (see Section 4.2.1), which performed a four-day on-site study to collect data from the fire scene. This investigation report presented full details of the incident based on the best available data and observations made from the site, and it also provided additional information according to the findings and results of analysis during the report development process. The investigation team documented and analysed various factors to learn lessons from the fire disaster and presented findings in order to reduce loss of life and property and prevent similar disasters from happening again.

Figure 6-15 displays part of the information that was recorded in the fire report. This nightclub held a Halloween party for high school students on that evening, and the official estimated number of attendees exceeded 400. This number of occupants was far greater than the permitted maximum occupancy load, which should have been 150 people according to the building code specified by the Gothenburg, Mölndal, Kungsbacka Fire Brigade.

(Figure removed for copyright reasons)

Figure 6-15 Snapshots from the Gothenburg dance hall fire report (Comeau and Duval, 2000)

The building configuration of the Gothenburg dance hall is displayed in Figure 6-16. The party was held in a nightclub on the first floor, and each end of the dance hall had an exit from which people could escape the building. The main entrance was located to the northwest directly towards the stairways to the exterior, and another emergency exit led people downstairs into a corridor on the ground floor. In addition, the nightclub had a series of windows on the north and south side of the walls. However, these windows were installed 2.2 metres above the floor, and the windows on the south were equipped with security bars to prevent intrusion. In other words, people had difficulty reaching these windows during the evacuation.

(Figure removed for copyright reasons)

Figure 6-16 The floor plan of the Gothenburg dance hall (Comeau and Duval, 2000)

Shortly before midnight, smoke from a fire that was located in the stairwell entered the hall from the southeast door. All the people present were trying to escape through the main exit to the northwest, because the southeast door was unavailable for use during the evacuation. According to witness statements, people were crowded shoulder to shoulder inside the dance hall, and they thought the smoke was from a cigarette. Therefore, they did not realise until it was too late that the smoke had spread quickly over the space.

A total of 63 people died; most were overcome by smoke inhalation. Forty-three victims were found near the main entrance on the northwest corridor, and an additional

20 bodies were found in a room (Room 203) in which they were hiding to escape from the fire. Furthermore, people jumped from windows so fire fighters found a number of occupants lying on the ground when they approached the building. Fire fighters also reported that bodies were packed at the entrance, so they had to remove them in order to rescue the rest of survivors inside. Overall, 180 people were injured in this fire, including the 50 to 60 people who were rescued by the fire fighters.

6.4.2 Station Nightclub Fire, West Warwick, Rhode Island, 20 February 2003 (Grosshandler *et al*., 2005)

The Rhode Island nightclub fire occurred on the night of 20 February 2003 in West Warwick, Rhode Island, USA. An investigation team from the National Institute of Standards and Technology (see Section 4.2.1), under the authority of the U.S. National Construction Safety Team Act, started to investigate the scene after the fire was extinguished. The report includes a general history of the building, a timeline of the incident and details of other emergency responses. In addition, the team used full scale experiments to recreate the fire scene and computer simulations to demonstrate the movement of fire, smoke and occupants. The objectives of this fire investigation were to find the causes of building failure, to evaluate evacuation and emergency response processes, to review building and fire codes and to make suggestions on the structural safety of buildings.

Figure 6-17 presents part of the information recorded in the fire report. The official number of occupants in the building at the time of the fire was 458, according to the fire report. The report mentioned several public documents stated the recommended occupancy loads in the Rhode Island nightclub were 225, 253 or 258 when tables and chairs were set up. Other figures, such as 317 and 404, were presented to reflect the possible increase in occupancy when tables and chairs were removed. Although different numbers were determined, the number of occupants present during the fire showed the building was significantly overloaded.

(Figure removed for copyright reasons)

Figure 6-17 Snapshots from the Rhode Island nightclub fire report (Grosshandler *et al*., 2005)

The building configuration of the Rhode Island nightclub is displayed in Figure 6-18. The nightclub was a single-floor building, and a total of four exits were located at the front and two sides of the building. The main entrance was a double door which was located to the north. Upon entering through the front door, people had to pass through a short entrance hall which led to the ticket checking area. Another two available emergency exits were located near the platform and the main bar. The fourth exit was located in the kitchen, which was mainly used by the staff and was not considered accessible to the guests during the evacuation. In addition to exits, windows were installed along the north side of the building, and those windows, along with those in the main bar and sunroom areas, became another important egress route after the main entrance was packed by most of the people who were trying to evacuate through the front door.

(Figure removed for copyright reasons)

Figure 6-18 The floor plan of the Rhode Island nightclub (Grosshandler *et al.*, 2005)

About 11:07pm, a band played the opening song along with pyrotechnics being set off. In a few seconds, hot particulates ignited the polyurethane foam on both sides of the platform at the back of the stage. Crowds soon realised that the fire was not a part of the show and started to evacuate. After that, the fire spread rapidly across the polyurethane foam and created a large amount of thick black smoke. An evacuation timeline was identified according to the video footage that was filmed by WPRI-TV, providing 05:43 minutes of various activities as the summary shows (Figure 6-19).

(Figure removed for copyright reasons)

Figure 6-19 Summary of evacuation timeline developed from video analysis of the Rhode Island nightclub fire report (Grosshandler *et al*., 2005)

Figure 6-20 displays the distribution of the victims; overall 96 people perished during the fire and more than 200 people were injured. The majority of deaths occurred near the main entrance: 31 people died along the entryway and 27 people died near the sunroom. Another 23 victims were found inside the building near the office, dart room and storage area. The fire investigators suggested two potential reasons for deaths occurring in the inner building. One reason was that guests were unfamiliar with the building and were trying to search for an exit or a safe area to stay. Another reason was that people became disoriented while heading for an exit.

(Figure removed for copyright reasons)

Figure 6-20 The number of deaths in each region of the Rhode Island nightclub (Grosshandler *et al*., 2005)

The fire report also recorded the number of occupants who successfully evacuated through each exit. The main entrance was considered to be the major evacuation route, and 90 occupants exited through this door. The second most frequently used exit was the side exit near the main bar, through which 46 occupants evacuated. The third available exit, the platform exit, was used by 20 occupants during the evacuation. Although the kitchen exit was not considered to be an egress route for patrons, 12 people (mostly employees) escaped through this exit. An overall 168 people successfully evacuated through exits, and another 79 occupants evacuated through windows.

6.4.3 Chicken Processing Plant, Hamlet, North Carolina, 3 September 1991 (Yates, 1991)

The Hamlet chicken processing plant fire occurred in the morning of 3 September 1991 in Hamlet, North Carolina, USA. This fire incident was scrutinised by an investigation team from United States Fire Administration (see Section 4.2.1). The report summarises information regarding events that happened during the incident and provides details about the building, fire and human behaviour. Figure 6-21 shows a summary of the key issues from the fire incident as part of the fire report. Their findings provide suggestions on life safety codes, safety usage of industry equipment and evacuation practices.

(Figure removed for copyright reasons)

Figure 6-21 Snapshots from the Hamlet chicken processing plant fire report (Yates, 1991)

The building was a one-storey brick and metal structure and the layout is displayed in Figure 6-22. A number of exterior doors were installed throughout the space, including at the main entrance on the east side of the building, a door at the southeast loading and trash compacting dock, a door in the break room, two doors in the equipment room and a door leading from the packing room to another exterior exit next to the freezer. Windows were placed at the east and west sides of the building according to the photographs, but the number and location of windows was not recorded in the floor map. In addition, no records of occupants using windows to evacuate were found in the fire report.

(Figure removed for copyright reasons)

Figure 6-22 Detailed floor plan of building from the Hamlet chicken processing plant fire report (Yates, 1991)

This building had previously been used for various food production operations, and 200 people were working in different positions and for various hours of the day. When the fire started at around 8:15am, 90 employees were working inside the building and the morning work shift of employees had just arrived. The fire ignited the hydraulic fluid fuel and soon created a rapid spread of heavy, black, hydrocarbon-charged smoke, which could disable a person in one or two breaths. In addition to fire conditions, most of the doors remained open in order to facilitate easy transport of products from one area to another during the working day. Therefore, the smoke spread rapidly through the building in a very short time, and thus all fatalities were found to have died by smoke inhalation rather than suffering direct flame injury.

Survivors said that there were no evacuation plans in place in the plant, and this is confirmed by the location of deaths (Figure 6-22). The largest number of deaths (12 people) and injuries (5 people) occurred in the cooler, which was adjacent to an exit at the loading dock. People tried to escape the smoke, but failed to close the sealed door, letting smoke infiltrate the enclosed space. Seven people could not immediately evacuate as they were trapped in the processing room between the fire and any possible egress route. Other people were unfortunately blocked by the locked exit and died during their search for an alternative route. A total of 25 people died and 54 people were injured in the Hamlet chicken processing plant fire.

6.5 Chapter Summary

This chapter introduced the final parameters that were determined for the evacuation model and the two modified navigation algorithms that were developed to increase the possibility of egress selections in the model. In addition, the model is set up to represent three specific fire disasters: the Gothenburg dance hall fire, the Rhode Island nightclub fire and the Helmet chicken processing plant fire, which were introduced according to the information from the fire report. The development of generic evacuation model, specific parameters, navigation algorithms and scenarios were presented in Chapter 5 and 6. The next three chapters display the simulation outcomes and compare the results to fire statistics recorded in the fire reports. Chapter 7 introduces an evaluation of the model by using the simulation results from the preliminary model.

7. Preliminary Simulation Outcomes and Evaluation

Introduction and Background	Contents of Evacuation Modelling	Developing Research Questions	Developing an Evacuation Model	Simulation Outcomes	Discussion	Conclusion and Further Work
Ch. 1	Ch. 2	Ch. 3	Ch. 4, 5 and 6	Ch. 7, 8 and 9	Ch. 10	Ch. 11

7.1 Introduction

The design and implementation of the evacuation model were introduced in Chapter 5 and 6. The following three chapters display the results of simulations using various tests. Firstly, the process for the evaluation and modification of preliminary models is introduced in this chapter. Chapter 8 displays the results of five main tests, which were based on the criteria identified in Section 3.5, namely realism, accuracy and processing speed, in order to determine whether the model is suitable for realisation or prediction type of evacuation modelling purpose. Finally, scenario parameters and building configurations are modified to simulate occupants' situations in different conditions of the fire disasters (Chapter 9).

This chapter displays the simulation results of preliminary evacuation models of the Gothenburg dance hall and the Rhode Island nightclub disasters, using human behaviour, victim count and location to identify whether the results are representative of events described in the fire investigation reports. After a first round of evaluation, the parameters and building layouts were changed in order to improve the evacuation model. In addition, the number of simulation runs was modified to ensure the model is stable and the results are statistically significant and reliable for further tests.

7.2 Evaluation of Preliminary Models

The first evacuation scenario used the Gothenburg dance hall fire as the basis for model development, and the building configuration (Figure 7-1) was designed according to the building scale provided in the fire report (see Figure 6-16). Different numbers of simulation runs, namely 100, 200 and 300, were tested to evaluate human behaviour in the preliminary model. Of these three numbers of simulation runs, the frequency outcomes of 300 runs presented the closest outcome to the shape of normal distribution. Therefore, this section displays the simulation outcomes of the whole evacuation process for 300 runs. In these 300 simulation runs, 400 pedestrian agents were randomly spread over the space (Section 6.2) and their starting positions were relocated before each simulation began. Other parameters such as the location of the origin of the fire, navigation algorithm and grid size remained the same over the 300 runs.

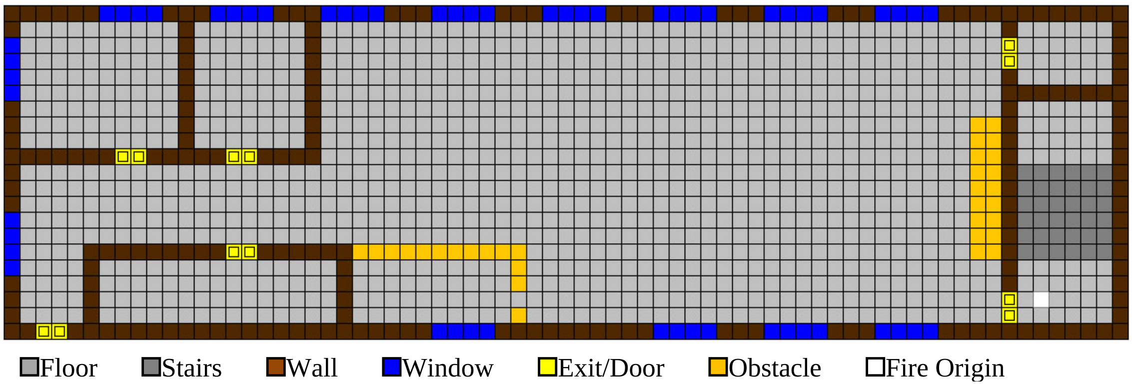


Figure 7-1 A 0.5 m^2 grid-based floor plan based on the original building scale in the Gothenburg dance hall fire report

After evaluating the evacuation scenario of the Gothenburg dance hall fire, the second building, the Rhode Island nightclub grid-based space (Figure 7-2), was built based on its scaled floor plan (see Figure 6-18). In addition, 500 pedestrian agents were randomly spread over the space (Section 6.2), and the number of simulation runs was increased to 500 for an increase in the statistical significance of results.

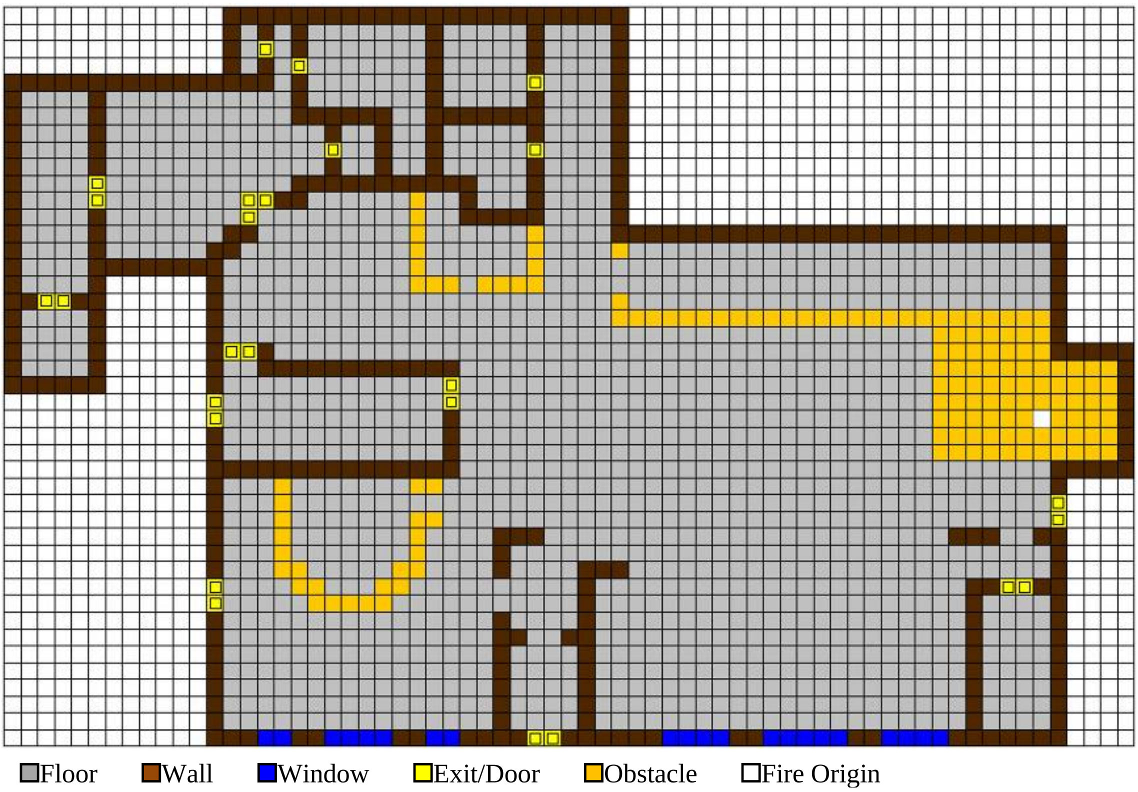


Figure 7-2 A 0.5 m^2 grid-based floor plan based on the original building scale in the Rhode Island nightclub fire report

The characteristics of and interactions between agents (pedestrian, door, and fire/smoke) in the model were established (Chapter 5) to simulate the human behaviours and evacuation phenomena identified in Section 4.4. The evaluation of the preliminary model is divided into two parts. Firstly, six human behaviours are evaluated to examine whether these agents behave correctly during the evacuation in the model. Secondly, the results of simulations are compared with fire statistics to establish similarity. For example, the number of deaths and injuries and the distribution of deaths are compared to the records in the fire report.

7.2.1 Evaluating the Preliminary Model using Human Behaviour

The following six human behaviours are evaluated in terms of the visualisations during the simulation and the average results from total simulation runs. In addition, the simulation outcomes are compared to the fire statistics, if applicable.

<u>1) Occupants evacuate through the main exits</u>

The fire agent started on the stairs behind an emergency door at the southeast of the building, which was assigned as the region in which the fire originated as mentioned in the fire report. When the simulation started, all pedestrian agents began to evacuate towards the main exit (Figure 7-3). These pedestrian agents stayed in the queue until they noticed the fire. After panicking, most of the pedestrian agents still continued to try to evacuate through the main exits.

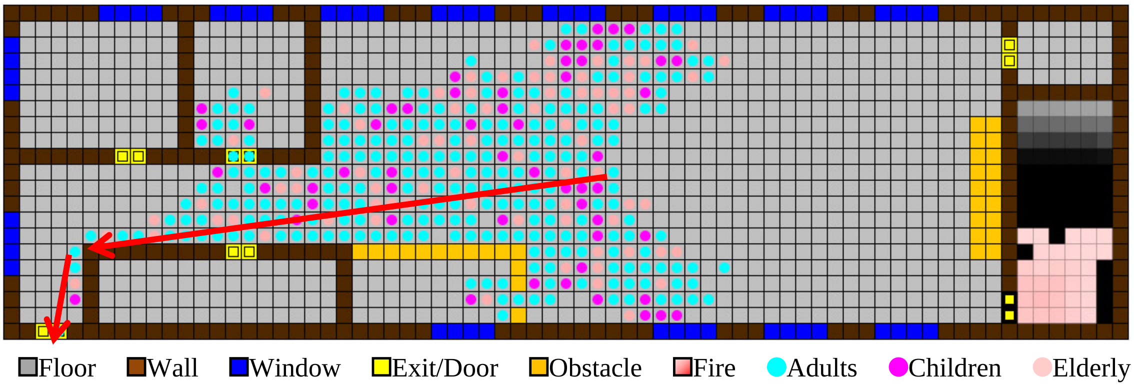


Figure 7-3 Pedestrian agents move toward the main exit at the southwest corner

The door agents record the number of pedestrian agents who successfully evacuated through the exit. Table 7-1 shows the average number of pedestrian agents who successfully evacuated through the main exit of the Gothenburg dance hall and the Rhode Island nightclub scenarios. In Table 7-1 and the remainder in this chapter, μ represents the average value of outputs, [min, max] represents the range of values, and σ represents standard deviation. Both navigation algorithms calculated over half of the total pedestrian agents evacuated through the main exit of the Gothenburg dance hall, which was the only exit that could be used in the actual fire disaster. In addition, 57.6% (A* algorithm) and 63.2% (Priority Queue Flood Fill algorithm) of total pedestrian agents evacuated through the main exit of the Rhode Island nightclub scenario, whereas the fire report recorded that around 56% to 66% occupants attempted to evacuate through the main entrance (Grosshandler *et al.*, 2005). The model produced reasonable results, as the average results were in the range of the fire statistics.

Table 7-1 The number of pedestrian agents who evacuated through the main exit using different navigation algorithms in the Gothenburg dance hall and the Rhode Island nightclub scenarios

Navigation Algorithms	Main Exit, Gothenburg Dance Hall	Main Exit, Rhode Island Nightclub
A* Algorithm	<u>μ = 221</u> [154, 270] ; σ = 20	<u>μ = 288</u> [182, 345]; σ = 24
Priority Queue Flood Fill Algorithm	<u>μ = 217</u> [169, 255] ; σ = 14	<u>μ = 316</u> [218, 386]; σ = 23

2) Occupants panic when they notice rapidly accumulating smoke

The moment pedestrian agents begin to display panic behaviour was described in Section 5.4.3. The first pedestrian agent who discovers a fire agent notifies others in the space, so all of the pedestrian agents change to panic behaviour at this point (Figure 7-4). While the pedestrian agents panic, most of them start to behave differently and some of them remain calm and patient. The model was able to simulate the moment of panic in both the Gothenburg dance hall scenario and the Rhode Island nightclub scenario in terms of the visualisation.

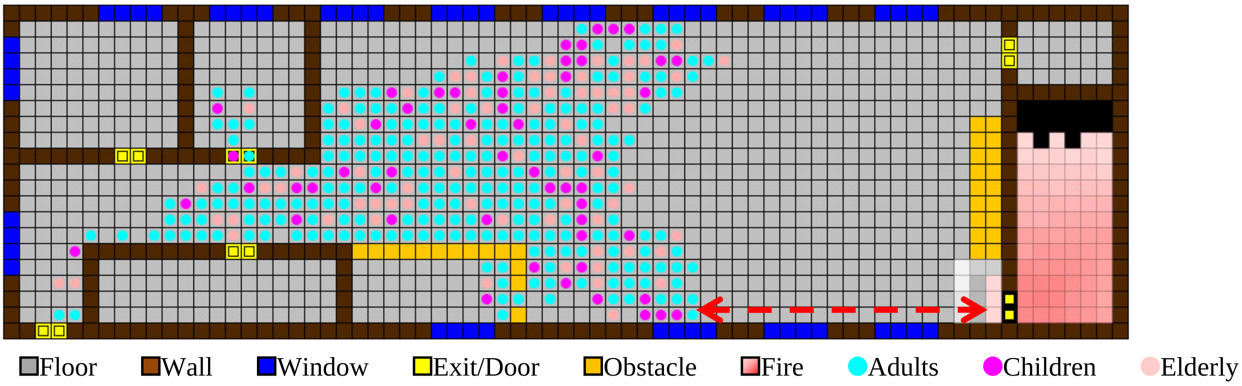
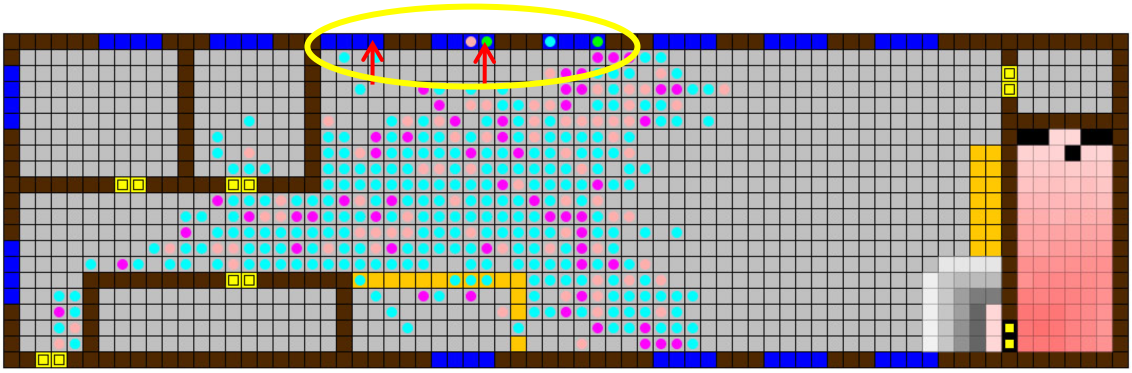


Figure 7-4 The moment pedestrian agents change to panic behaviour after seeing smoke come out from the door

3) Occupants evacuate through windows

Some of the pedestrian agents try to escape through windows after they panic. In the Gothenburg dance hall building, security bars were installed on the south side of windows to prevent people from intruding from outside. These windows restricted occupants' access during the evacuation, so this model blocked these windows before the simulation started. In addition, the model assumes that people who escape through windows are injured and rescued by fire fighters, displaying them as green dots in Figure 7-5.



Floor Wall Window Exit/Door Obstacle Fire Adults Children Elderly Rescued

Figure 7-5 Pedestrian agents move to windows to jump or wait to be rescued

The number of pedestrian agents who are rescued at the windows is calculated after the simulation. Table 7-2 shows the average number of pedestrian agents who escape through windows in the two evacuation scenarios. The fire reports lack information about the number of people who escaped through windows, only mentioning that people did jump from windows or were rescued by fire fighters via ladders through windows. Therefore, this behaviour cannot be compared to the real fire statistics, because an accurate number of people who used the windows to escape cannot be defined.

However, a significant issue occurred in the Rhode Island nightclub evacuation scenario, because no pedestrian agents were recorded escaping through windows in any simulation run. This issue was then identified and addressed after evaluation of the preliminary models (Section 7.3.1).

Table 7-2 The number of pedestrian agents who escaped through windows using different navigation algorithms in the Gothenburg dance hall and the Rhode Island nightclub scenarios

Navigation Algorithms	**Windows, Gothenburg Dance Hall**	**Windows, Rhode Island Nightclub**
A* Algorithm	$\underline{\mu = 50}$ [29, 78] ; $\sigma = 8$	N/A
Priority Queue Flood Fill Algorithm	$\underline{\mu = 89}$ [60, 120] ; $\sigma = 12$	N/A

<u>4) Occupants find a place to hide</u>

When occupants panic, they might try to find shelter in which to hide. In the Gothenburg dance hall, only one room was accessible to occupants and other rooms were locked during the event. Therefore, the model blocked these doors and areas to prevent pedestrian agents from entering during the simulation. Figure 7-6 shows a number of pedestrian agents were hiding in a room of the Gothenburg dance hall.

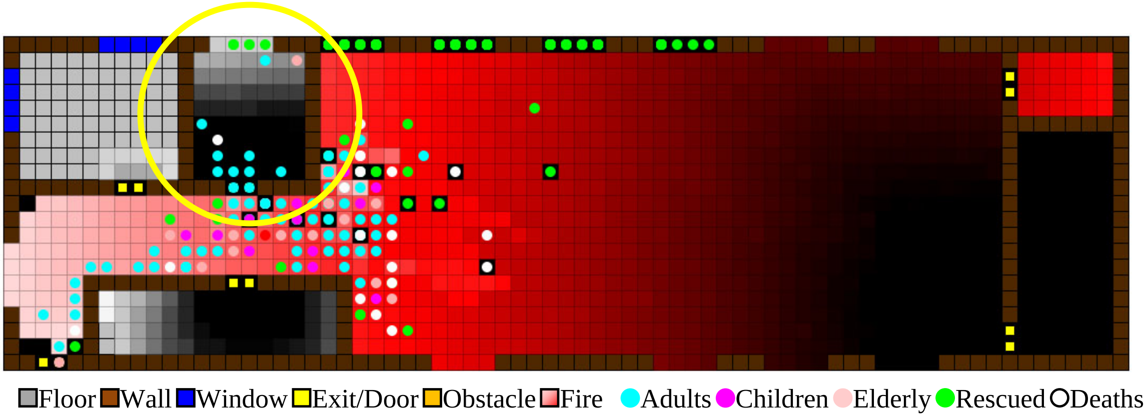


Figure 7-6 Pedestrian agents move into a room and find a place to hide

The model assumes that pedestrian agents who decide to hide would stay at the location until they were rescued or died. Evaluation of this behaviour compared the simulation results with the statistics from the Gothenburg dance hall and the Rhode Island nightclub fire reports. Table 7-3 shows the average number of deaths that occurred in the room of the Gothenburg dance hall scenario and various secluded rooms of the Rhode Island nightclub scenario. The similarity of the results, which are calculated by the average number divided by the fire statistics, shows how closely the results represented the actual fire disasters. The similarity of the outcomes with the Gothenburg dance hall scenario was relatively low, but the results of the Rhode Island nightclub scenario were almost the same as the actual fire. A number of parameters are adjusted after the preliminary tests to increase the similarity of simulation results, and final parameters were displayed in Table 6-1.

Table 7-3 Average numbers of pedestrian agents who died in rooms using different navigation approaches in the Gothenburg dance hall model and the Rhode Island nightclub model

Navigation Algorithms	Deaths in a Room, Gothenburg Dance Hall	Death in Rooms, Rhode Island Nightclub
A* Algorithm	$\underline{\mu = 3}$ [0, 13] ; $\sigma = 3$	$\underline{\mu = 9}$ [3, 22]; $\sigma = 3$
Similarity (%)	15.0%	71.4%
Priority Queue Flood Fill Algorithm	$\underline{\mu = 2}$ [0, 10] ; $\sigma = 2$	$\underline{\mu = 7}$ [1, 18]; $\sigma = 3$
Similarity (%)	10.0%	100.0%
Fire Report Statistics	20	7

5) Occupants search for alternative routes

The definition of pedestrian agents searching for alternative routes in the model is when they change their egress routes from the main exits to emergency exits. Table 7-4 shows the usage of emergency exits, displaying the numbers of pedestrian agents who passed through the doors. The fire started behind the emergency exit in the Gothenburg dance hall fire disaster, so nobody escaped through this exit during the actual fire evacuation. As the numbers show in the table, some of the pedestrian agents evacuated through the emergency exit when using the Priority Queue Flood Fill algorithm. Looking into the simulations, 115 out of 300 simulation runs calculated one to five people escaping through this exit, which should not happen due to the spread of fire.

In the Rhode Island nightclub, the exit in the kitchen was not considered to be an egress route for the occupants inside the nightclub, because the exit was located inside the kitchen and was unknown to customers. Therefore, the model blocked the kitchen area and doors to avoid access by pedestrian agents. In addition to the issue that happened in the Gothenburg dance hall scenario, the average number of evacuees at emergency exits in the Rhode Island nightclub scenario is very different between the two navigation algorithms. As a result, this behaviour was modified after the preliminary evaluation (Section 7.3.1).

Table 7-4 The number of pedestrian agents who evacuated through emergency exits using different navigation algorithms in the Gothenburg dance hall and the Rhode Island nightclub scenarios

Navigation Algorithms	Emergency Exits, Gothenburg Dance Hall	Emergency Exits, Rhode Island Nightclub
A* Algorithm	N/A	$\mu = 65$ [43, 90]; $\sigma = 9$
Priority Queue Flood Fill Algorithm	$\mu = 1$ [0, 5] ; $\sigma = 1$	$\mu = 38$ [23, 56]; $\sigma = 5$

6) Occupants escape from the fire or smoke

The model assumes that pedestrian agents know whether there is a fire/smoke agent present at their egress targets, so they change their directions before they move to the destination. This behaviour significantly occurred in the Gothenburg dance hall scenario, which simulated 100% of pedestrian agents avoiding moving to the emergency exit where the fire started when the A* algorithm was used and 99.8% of pedestrian agents moving correctly according to the Priority Queue Flood Fill algorithm. In addition, pedestrian agents who decided to escape through windows selected windows that were further from the fire (Figure 7-7).

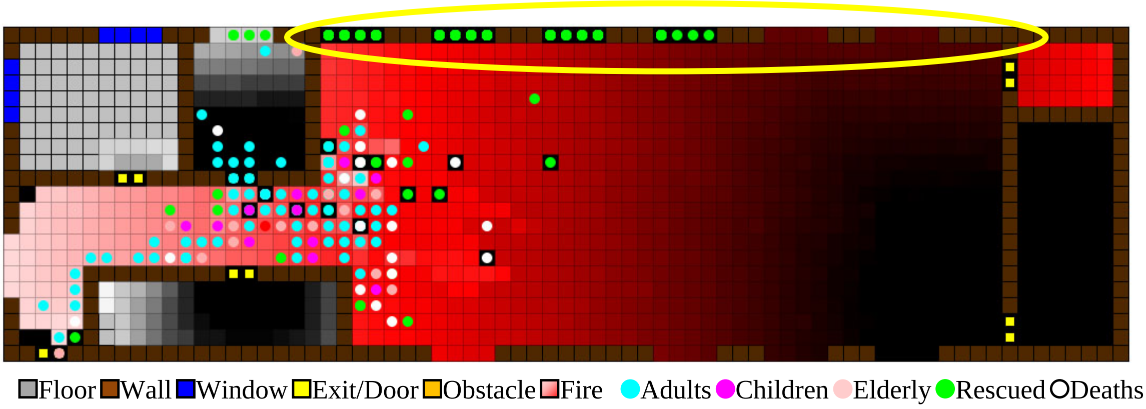


Figure 7-7 Pedestrian agents selected windows which were further from the fire, and most of the pedestrian agents moved in the opposite direction to the fire towards the main exit at the south west of the building

A modelling issue related to windows in the Rhode Island nightclub scenario was described in the behaviour of "occupants evacuate through windows" (Section 7.2.1), so it was difficult to identify if pedestrian agents behaved correctly according to the simulation results. Table 7-5 shows the overall occupant evacuation times at the platform exits were far shorter than the times at other exits in both navigation algorithms, and thus it could be identified that pedestrian agents avoided using the exit because of the fire agents spread over the space.

Table 7-5 Overall evacuation time that pedestrian agents spent to evacuate through each exit or windows using different navigation algorithms in the Rhode Island nightclub scenario

Navigation Algorithms	Front Entrance	Main Bar Side Exit	Platform Exit	Windows
A* Algorithm	436 seconds	104 seconds	35 seconds	N/A
Priority Queue Flood Fill Algorithm	451 seconds	95 seconds	37 seconds	N/A

7.2.2 Evaluating the Preliminary Model using Victims

Two main results from the simulations were compared to the fire statistics. Firstly, the number of deaths and injuries was used to determine the level of risk caused by the specific number of occupants in the buildings. Secondly, the location and number of deaths were used to identify the areas of risk in the buildings.

1) Number of deaths and injuries

Pedestrian agents inhale smoke when they are surrounded by fire/smoke agents, and they might faint or die when they exceed their carbon monoxide tolerance level (Section 5.4.6). The number of deaths was incremented after each pedestrian agent died. In addition to deaths, the number of injuries in the simulations was also recorded, including the pedestrian agents who jump or escape through windows and those who are rescued by fire fighters after they faint inside the building. Table 7-6 shows the average number of deaths and injuries in the Gothenburg dance hall scenario. The average number of deaths was 96.8% (A* algorithm) and 74.6% (Priority Queue Flood Fill algorithm), similar to the actual number of deaths (63) in the actual disaster. Additionally, the model simulated 63.9% (A* algorithm) and 75.0% (Priority Queue Flood Fill algorithm) similarities with the actual number of injuries (180).

Table 7-6 The numbers of deaths and injuries using different navigation algorithms in the Gothenburg dance hall scenario

Navigation Algorithms	**Deaths**	**Injuries**
A* Algorithm	$\mu = 65$ [37, 110]; $\sigma = 12$	$\mu = 115$ [77, 153]; $\sigma = 12$
Similarity (%)	96.8%	63.9%
Priority Queue Flood Fill Algorithm	$\mu = 47$ [25, 73]; $\sigma = 8$	$\mu = 135$ [99, 170]; $\sigma = 12$
Similarity (%)	74.6%	75.0%
Fire Report Statistics	63	180

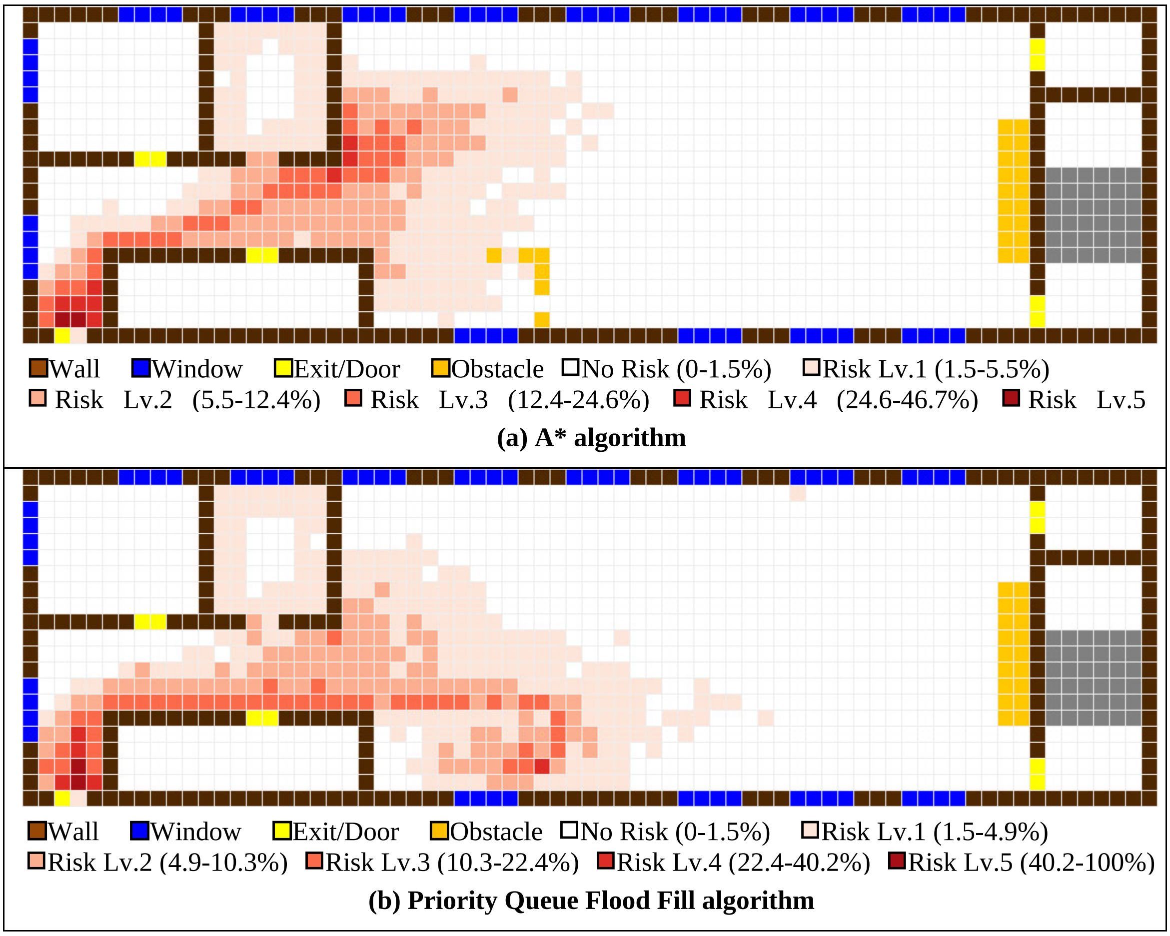
In the Rhode Island nightclub scenario, a comparison of the outcomes of the simulations and the actual fire statistics shows similarities of 82.0% (A* algorithm) and 80.9% (Priority Queue Flood Fill algorithm) for deaths and 32.2% and 31.7% for injuries (Table 7-7). However, a number of modelling issues that might influence the simulation results were identified in the Rhode Island nightclub model (Section 7.2.1). Therefore, further comparisons are displayed in Section 8.2.3 after modification.

Table 7-7 Average number of deaths and injuries using different navigation algorithms in the Rhode Island nightclub scenario

Navigation Algorithms	**Deaths**	**Injuries**
A* Algorithm	$\mu = 73$ [44, 121]; $\sigma = 14$	$\mu = 74$ [43, 129]; $\sigma = 13$
Similarity (%)	82.0%	32.2%
Priority Queue Flood Fill Algorithm	$\mu = 72$ [38, 126]; $\sigma = 13$	$\mu = 73$ [34, 119]; $\sigma = 13$
Similarity (%)	80.9%	31.7%
Fire Report Statistics	89	230

2) Distribution of deaths

After establishing the absolute number of deaths and injuries, this section displays the distribution of deaths on grid-based building maps. In order to display choropleth maps, the natural breaks classification was used as the values identified unusual class boundaries, and thus define breaks in which large changes in value occur (de Smith *et al.*, 2007). In addition, the number of classes is usually set between 5 to 9 categories, so for the simulation outcomes it was decided to use six classes to classify different risk levels. Figure 7-8 presents the possibility of death location in the Gothenburg dance hall scenario, and it shows that the highest number of deaths occurred near the main exit; other deaths occurred along the corridor, and some died in the room in both calculations.



(a) A* algorithm

(b) Priority Queue Flood Fill algorithm

Figure 7-8 The potential death locations in the Gothenburg dance hall fire scenario

In the Gothenburg dance hall fire report, 43 out of 63 deaths occurred on the corridor near the main entrance, and others died in the room (Section 6.4.1). These two areas were considered to be high-risk areas in the fire disaster, but the room was identified as a low-risk (risk level 0 and 1) area according to the choropleth map (Figure 7-8). Therefore, it was concluded that the simulation results differed from what happened in real life. In addition, the distribution shows the differences between death locations in the two algorithms: the distribution of high-risk death locations formed in a diagonal straight line from the main exit when the A* algorithm was used, whereas most of the deaths occurred along the wall when calculating using the Priority Queue Flood Fill algorithm. To compare the simulation results of two algorithms to fire statistics at a specific location, regions are defined based on the distribution of deaths in both choropleth maps and fire reports. For example, Figure 7-9 shows the region classification of the Gothenburg grid-based dance hall scenario as region 1 (corridor) and region 2 (room) according to the visualisation of the results in Figure 7-8 and the locations of deaths in the space (the room and the corridor) that were recorded in the fire report.

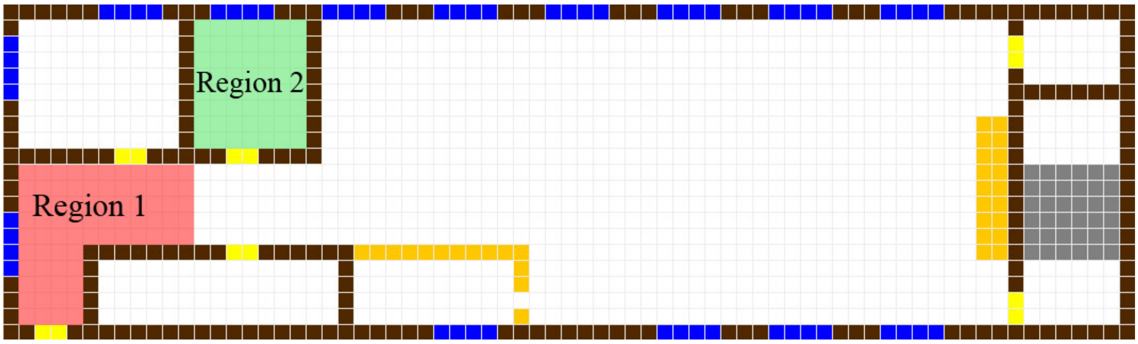


Figure 7-9 Region identification based on the distribution of deaths displayed on a choropleth map and the information from the Gothenburg dance hall fire report

Although the average numbers of total deaths in the simulations of the Gothenburg dance hall scenario showed similarities of over 74% when compared to the total number of deaths in the real fire (see Table 7-6), the distribution of deaths on the choropleth map display a big difference between the simulations and reality. According to the results shown in Table 7-8, none of the outcomes among the classified regions and navigation calculating methods show a similarity of anything like 74%.

Table 7-8 Average numbers of deaths that occurred in regions 1 and 2 (see Figure 7-9) using different navigation algorithms in the Gothenburg dance hall scenario

Navigation Algorithms	Region 1 (Corridor)	Region 2 (Room)
A* Algorithm	$\mu = 31$ [11, 70]; $\sigma = 11$	$\mu = 3$ [0, 13]; $\sigma = 3$
Similarity (%)	72.0%	15.0%
Priority Queue Flood Fill Algorithm	$\mu = 20$ [3, 55]; $\sigma = 7$	$\mu = 2$ [0, 10]; $\sigma = 2$
Similarity (%)	46.5%	10.0%
Fire Report Statistics	43	20

In order to show the percentage of deaths that might occur in a region and highlight potential risk areas in the space, the death occurrence in each region is calculated by dividing the number of deaths in a region by the total number of deaths in the building. The higher the percentage of death occurrence, the more deaths occurred in this region. For example, approximately 29.8% (A* algorithm) of total deaths in the Gothenburg dance hall scenario were found in the corridor, or in other words, there was a 29.8% possibility that a death would occur in the corridor (Table 7-9). Furthermore, this table also shows a decrease in the similarities when presenting death occurrences by location rather than victim counts (see Table 7-8).

Table 7-9 Average death occurrences that occurred by location in the Gothenburg dance hall scenario shown in percentages using different navigation algorithms

Navigation Algorithms	**Region 1 (Corridor)**	**Region 2 (Room)**
A* Algorithm	μ = 29.8% [2.0%, 58.2%]; σ = 11.1%	μ = 4.9% [0%, 26%]; σ = 4.7%
Similarity (%)	43.6%	15.5%
Priority Queue Flood Fill Algorithm	μ = 28.1% [4.9%, 66.2%]; σ = 10.0%	μ = 4.8% [0%, 23.7%]; σ = 4.4%
Similarity (%)	41.1%	15.1%
Fire Report Statistics	68.3%	31.7%

The above figures and tables displayed the simulation results of the Gothenburg dance hall scenario, and the following figures and tables present the results for the Rhode Island nightclub scenario. Figure 7-10 shows the possibility of death in each location in the nightclub, and the entryway near the main exit of the nightclub was identified as a high-risk area (risk level 4 and 5). Other occupants died near the entryway and in several rooms in both calculations.

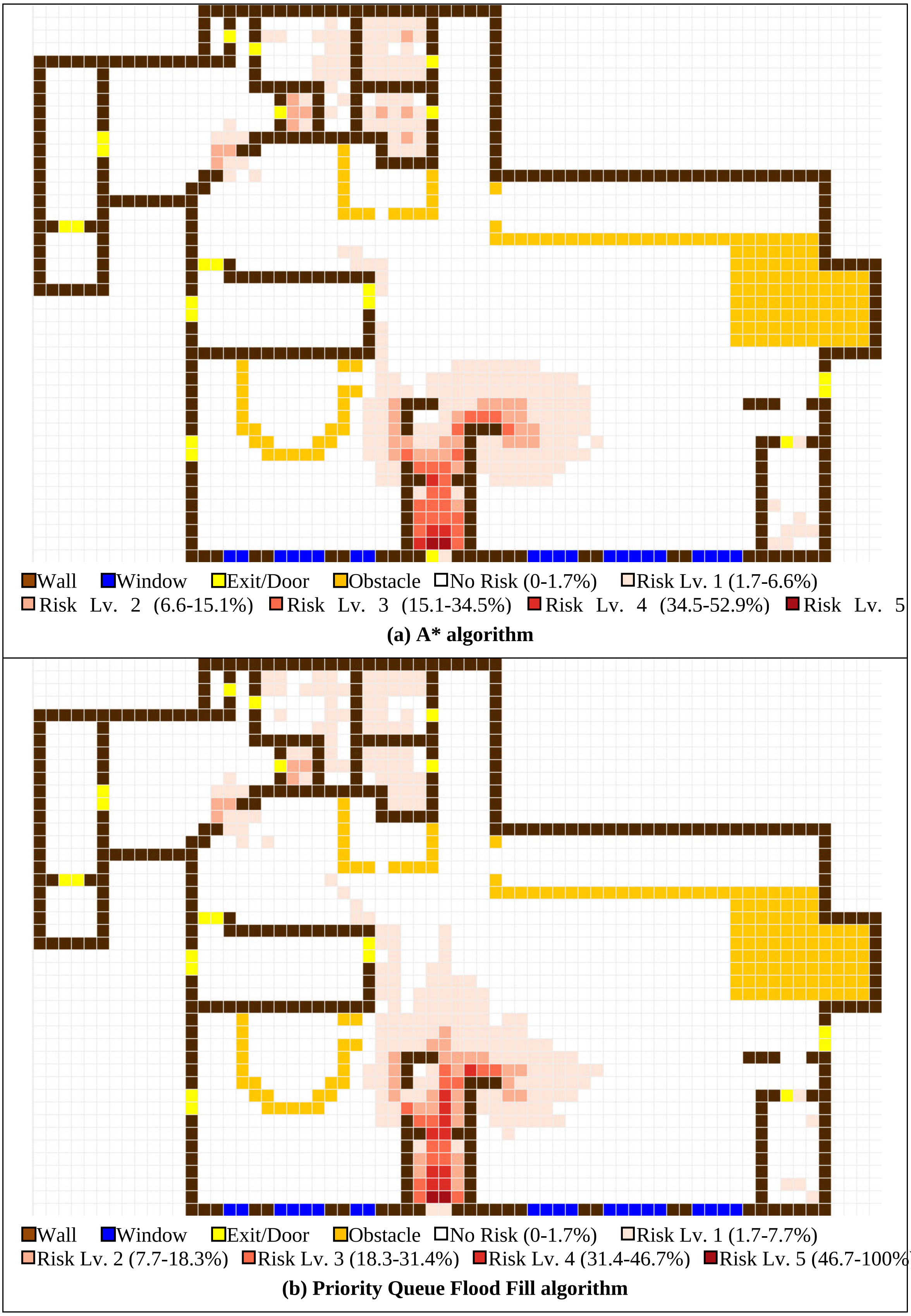


Figure 7-10 The potential death locations in the Rhode Island nightclub fire scenario

According to the fire report, 96 people died in the Rhode Island nightclub fire, 31 of them perished along the entryway, 27 occupants died near the Sunroom, and the remainder of the bodies were found in the office, the Dart room and storage area (Section 6.4.2). Five regions were identified in terms of the choropleth map (Figure 7-10) and the floor map of deaths in the fire report (Figure 6-20). The final region classification is displayed in Figure 7-11, representing the entryway to the front entrance (region 1), rooms inside the building (region 2), storage area (region 3), the Dart room (region 4) and the Sunroom (region 5).

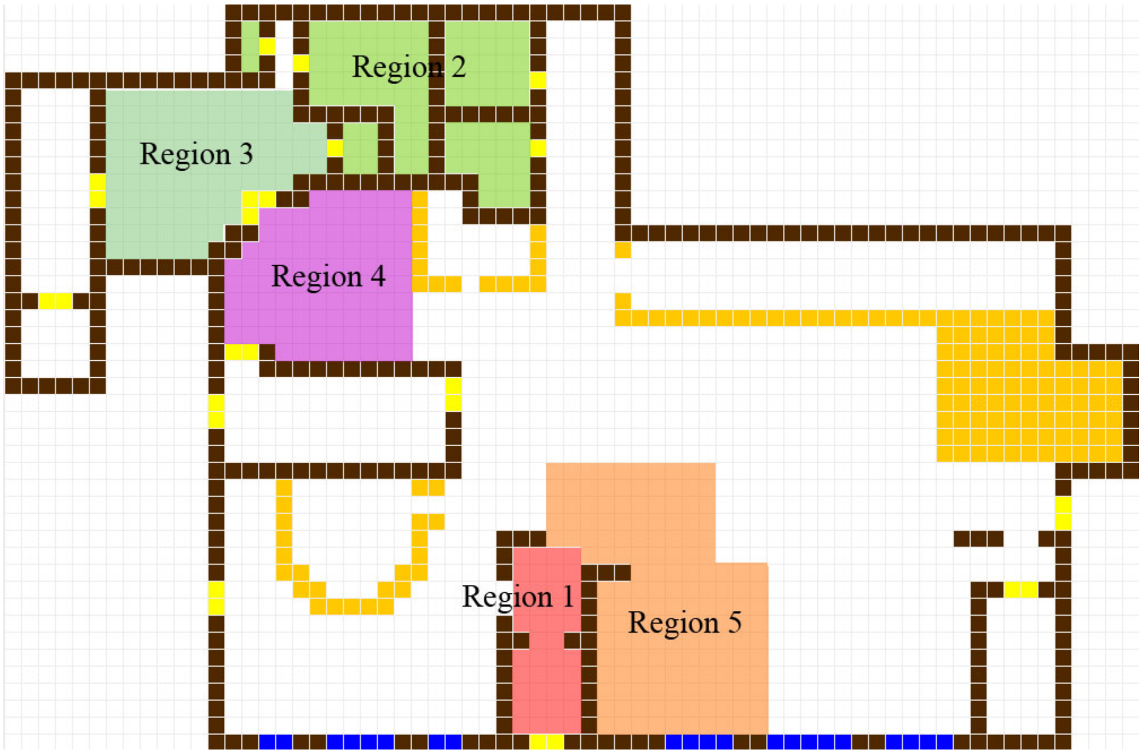


Figure 7-11 Region identification based on the distribution of deaths displayed on a choropleth map and the victim map in the Rhode Island nightclub fire report

Table 7-10 displays the number of deaths in each identified region, showing several positive results from the simulation runs. For example, the calculated number of deaths that occurred in the entryway near the front entrance showed a 100% match when compared with the fire statistics. In addition, the result was over 71% similar to reality when the number of deaths in the rooms was calculated by the A* algorithm, and showed 100% similarity when the Priority Queue Flood Fill algorithm was used. Over half of the actual number of deaths occurred in the Sunroom in the simulation. On the other hand, the Rhode Island nightclub model calculated fewer deaths in the Dart room and the storage area, which showed a similarity of less than 25%. Therefore, the parameters of pedestrian agent behaviour was modified to balance the differences between the number of deaths in regions 3 and 4 (Section 7.3.1).

Table 7-10 Average numbers of deaths that occurred in regions 1 to 5 (see Figure 7-11) using different navigation algorithms in the Rhode Island nightclub scenario

Navigation Algorithms	**Region 1 (Entryway)**	**Region 2 (Rooms)**	**Region 3 (Storage Area)**	**Region 4 (Dart Room)**	**Region 5 (Sunroom)**
A* Algorithm	$\mu = 31$ [8, 78] $\sigma = 12$	$\mu = 9$ [3, 22] $\sigma = 3$	$\mu = 1$ [0, 7] $\sigma = 1$	$\mu = 2$ [0, 8] $\sigma = 2$	$\mu = 16$ [4, 31] $\sigma = 5$
Similarity (%)	100%	71.4%	10%	22.2%	59.3%
Priority Queue Flood Fill Algorithm	$\mu = 31$ [2, 84] $\sigma = 12$	$\mu = 7$ [1, 18] $\sigma = 3$	$\mu = 1$ [0, 7] $\sigma = 1$	$\mu = 2$ [0, 10] $\sigma = 1$	$\mu = 15$ [2, 31] $\sigma = 5$
Similarity (%)	100%	100%	10%	22.2%	55.6%
Fire Report Statistics	31	7	10	9	27

Although the number of deaths in regions 1 and 2 accurately simulated the numbers that occurred in the Rhode Island nightclub fire, the death occurrence similarities in regions 1 and 2 decreased by approximately 20-35% (Table 7-11). In contrast, the similarities increased by about 5-15% in regions 3 to 5. In conclusion, the numbers of deaths in the storage room and the Dart room were far lower than the numbers in the actual fire disaster. Therefore, the model was modified to increase the similarities in these two regions.

Table 7-11 Average death occurrences that occurred by location in the Rhode Island nightclub scenario shown in percentages using different navigation algorithms

Navigation Algorithms	**Region 1 (Entryway)**	**Region 2 (Rooms)**	**Region 3 (Storage Area)**	**Region 4 (Dart Room)**	**Region 5 (Sunroom)**
A* Algorithm	$\mu = 41.5\%$ [14.0, 73.6] $\sigma = 10.4$	$\mu = 12.9\%$ [3.9, 24.6] $\sigma = 4.1$	$\mu = 1.7\%$ [0, 10.0] $\sigma = 2.0$	$\mu = 3.1\%$ [0, 10.9] $\sigma = 2.2$	$\mu = 22.1\%$ [5.7, 42.6] $\sigma = 6.8$
Similarity (%)	80.7%	36.7%	15.2%	30.7%	72.9%
Priority Queue Flood Fill Algorithm	$\mu = 41.8\%$ [5.3, 72.5] $\sigma = 10.6$	$\mu = 10.3\%$ [1.1, 25.5] $\sigma = 4.1$	$\mu = 1.7\%$ [0, 9.8] $\sigma = 1.8$	$\mu = 2.6\%$ [0, 13.7] $\sigma = 2.0$	$\mu = 21.2\%$ [5.1, 49.2] $\sigma = 6.9$
Similarity (%)	79.9%	69.6%	15.2%	25.7%	70.0%
Fire Report Statistics	34.8%	7.9%	11.2%	10.1%	30.3%

7.3 Model Modification and Simulation Run Time Decision

The previous section presented a number of preliminary simulation results to identify whether the developed evacuation model recreated an evacuation scenario that was close to what actually happened in the fire disaster. This section introduces a number of issues and parameters that were modified and improved to simulate correct human behaviour, output better results that are closer to the fire statistics and balance the differences between the results from the two algorithms. Next, different number of simulation runs was executed to show if the model results display as a stable value so that the value can be representative of multiple runs and used for statistical tests.

7.3.1 Model modifications and improvements

This section outlines the modifications and improvements that were made to address the issues in the preliminary model and simulate better results. Table 7-12 displays a number of issues that were identified in the preliminary model in terms of the related behaviour in Section 7.2.

Table 7-12 Issues that occurred in the model in terms of the related behaviour in Section 7.2

Issues	Related Human Behaviour
No pedestrian agents evacuated through windows	Occupants evacuate through windows
Pedestrian agents were evacuating toward the fire/smoke agents	Occupants search for alternative routes Occupants escape from the fire or smoke
Low similarity between simulation results and fire statistics	Occupants find a place to hide Number of injuries Distribution of deaths

Firstly, the issue of pedestrian agents who were not evacuating through windows in the Rhode Island nightclub scenario was addressed by manually checking the movement and egress selection of those agents. Secondly, the interactions between pedestrian, door and fire/smoke agents were improved to avoid pedestrian agents moving to a door that is on fire. Thirdly, various parameters such as the number of pedestrian agents in the Rhode Island nightclub scenario, individual carbon monoxide tolerance levels, the speed of the spread of smoke, decisions regarding egress routes and building configuration (Figure 7-12) were modified to reduce the differences between the simulation results and the fire statistics, as well as between the two algorithms.

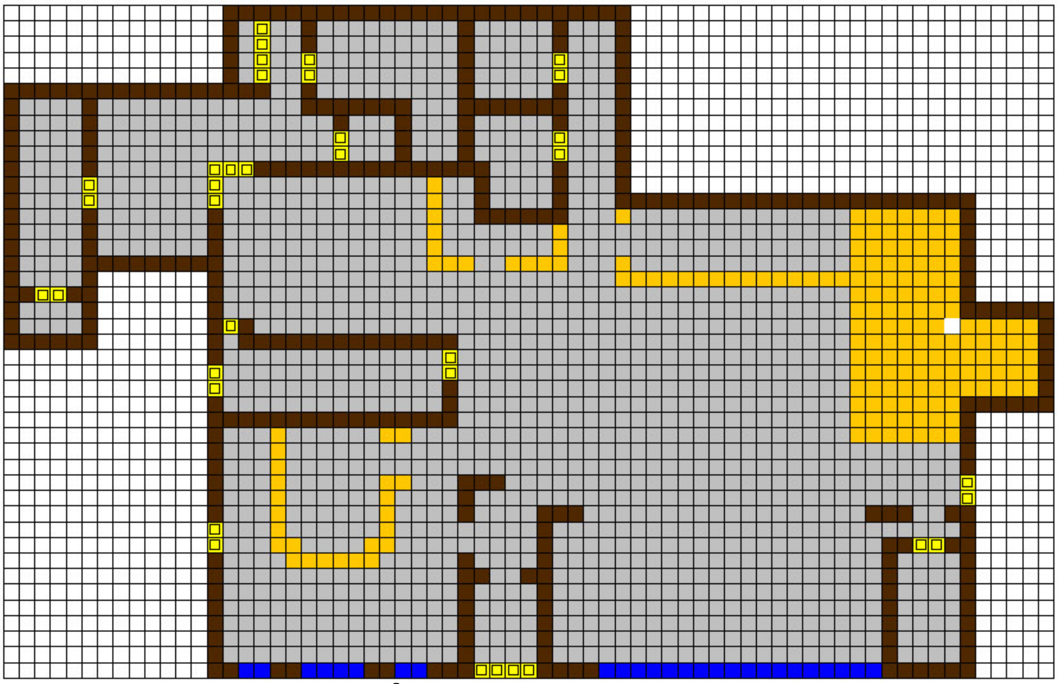


Figure 7-12 A modified 0.5 m^2 grid-based floor map of the Rhode Island nightclub

7.3.2 Determination of sample size and statistical test

The final model was set up to simulate three different fire disasters (Section 6.4) and it was necessary to establish a number of parameters before the start of the simulations (Section 6.2). During the simulation runs, these parameters are fixed and each simulation calculates unique results in terms of the characteristics of and interactions between agents. Therefore, an evacuation scenario is required to simulate multiple runs in order to ensure the results of further simulations of different scenarios are precise and accurate. The evacuation model of this thesis calculated the number of runs based on a sample size determination (Johnson, 2009), and the formula to represent a sample size 'n' for proportion is:

$$n = \frac{Z^2 \times p \times q}{\sigma^2} \tag{7.1}$$

where

Z: Standard score for the desire confidence level

p: % of deaths

q: % of survivors (1－p)

σ: margin of error that is expected

The model determined sample sizes (simulation runs) under a fixed condition of 95% confidence level (Z=1.96), which is the most commonly used confidence level (Utts and Heckard, 2011). Percentages of p and q represent deaths and survivors based on the percentage of victims in three different fire disasters. The previous three variables are deterministic values, but it is unsure that which percentage of precision (σ) can produce accurate and stable results. Therefore, different numbers of runs were conducted to identify the most suitable percentage of precision for the formula.

A total number of 1000 runs were simulated in the evacuation model using the Gothenburg dance hall scenario. The model simulated unique results in each run, so an average value was calculated to represent the overall result of the model. Figure 7-13 displays the trend of mean and standard deviations that were calculated from 1 to each number of run. The results show that the values became stable after a certain number of simulation run, which was approximately 325. Subsequently, a ±4% precision (σ) was considered the expected error range to establish reliable measures of outcome for the following evacuation scenarios.

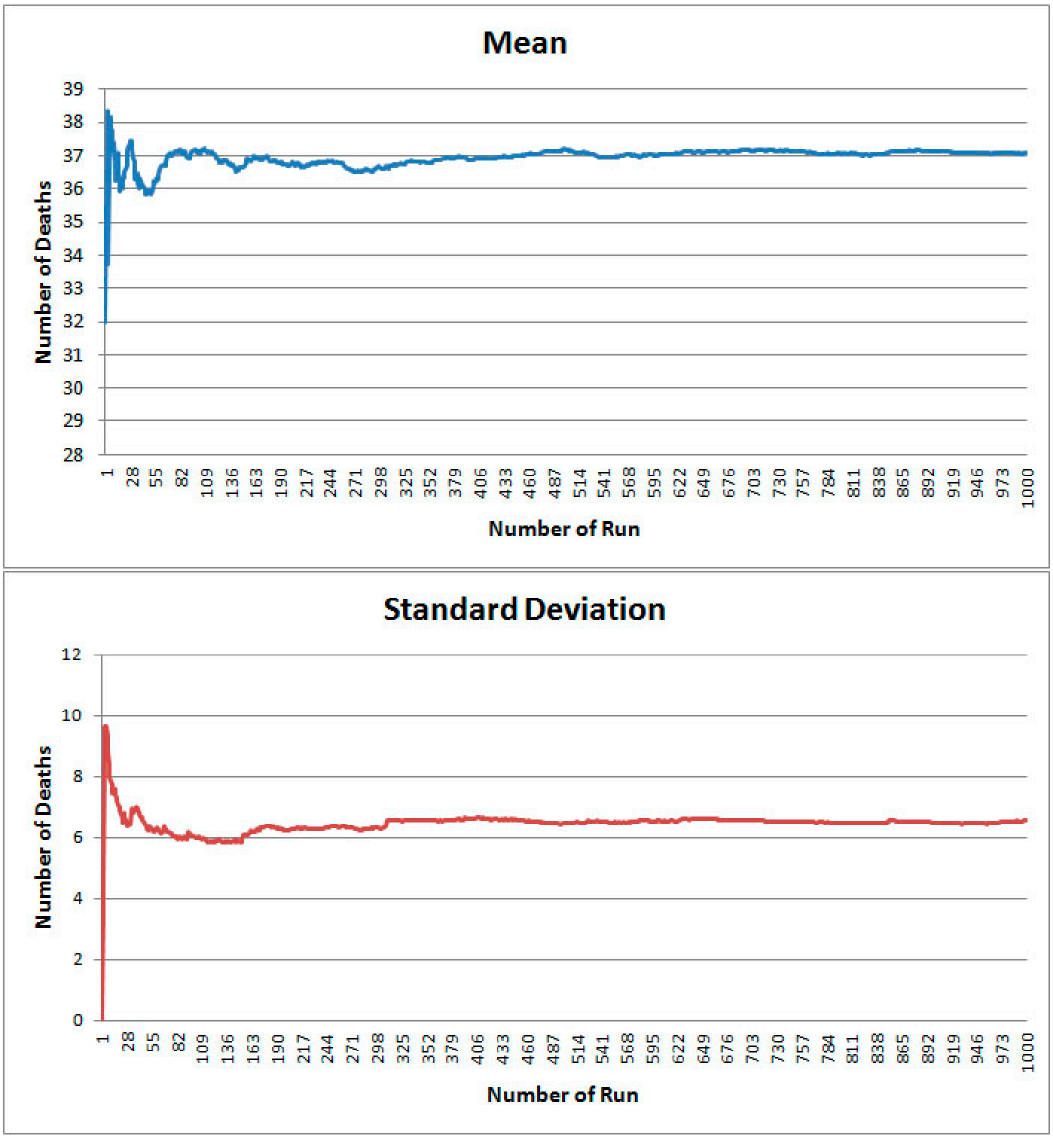


Figure 7-13 Average values and standard deviations of the dependent variables using 1 to 1000 of the runs in the Gothenburg dance hall scenario

Once the parameters in the sample size formula are defined, the model simulates the number of run based on the calculation. Firstly, in the Gothenburg dance hall fire 16% of occupants died (p) and 84% of occupants survived (q) the event. According to the formula, the Gothenburg dance hall model requires at least 322 runs for evaluation. Secondly, 22% of occupants died (p) and 78% survived (q) in the Rhode Island nightclub fire, so the model requires more than 412 runs to evaluate the results. Finally, the Hamlet chicken processing plant fire caused 25 deaths, representing 28% of the total occupants (p). Therefore, the formula calculated that the model requires more than 484 runs in order to evaluate the results effectively.

In order to simplify the simulation runs in terms of ease of calculation, the number of runs in each fire evacuation scenario was further increased to the next hundred. In addition, the greater the number of simulation runs, the more results can be included in the statistical analysis for testing the simulation outcomes. Therefore, the Gothenburg dance hall scenario used 400 runs, the Rhode Island nightclub scenario used 500 runs and the Hamlet chicken processing plant scenario used 500 runs in the model to output different simulation results that might occurred in the fire events.

A statistical analysis, t-test, was expected to identify if two sets of results (mean values) that were calculated by different navigation algorithms are significantly different from each other. However, this test is not suitable for this thesis as t-test can only be used when the results are normally distributed. When an extreme case occurs, for example, the model calculated pedestrian agents spent 25 seconds (mean value) at the emergency exit although a high frequency of no evacuee used this exit over the simulation runs (Figure 7-14). Therefore, a non-parametric statistical hypothesis test, the Wilcoxon signed ranks test, is proposed as an alternative test while the population cannot be formed as a normal distribution. In order to use the Wilcoxon signed ranks test, the results that are displayed in following chapters use median values instead of mean values.

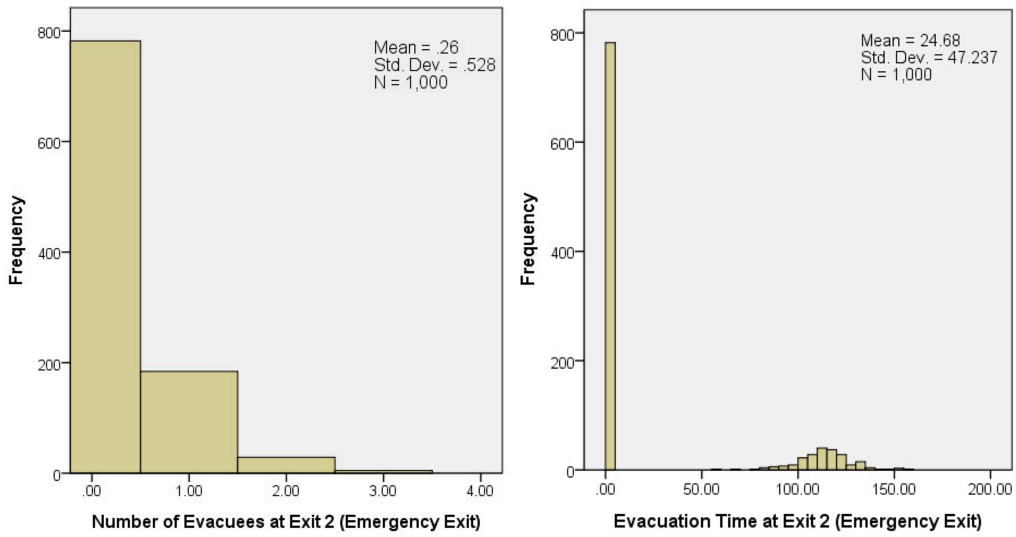


Figure 7-14 Frequency distribution of the simulation results for the number of evacuees and evacuation time at emergency exit in the Gothenburg dance hall scenario

7.4 Chapter Summary

This chapter presented the simulation results of the preliminary model, and the model was evaluated in terms of human behaviour and evacuation phenomena. The results of evaluation using human behaviour (Section 7.2.1) are summarised in Table 7-13. In addition, the number and distribution of victims were compared to the fire statistics. This comparison was examined to ensure models could successfully simulate an actual fire that occurred in similar conditions. The results of the evaluation using victims (Section 7.2.2) are summarised in Table 7-14.

Table 7-13 The issues occurred while evaluating by human behaviour in the preliminary model.

Human Behaviour	Issues
Occupants evacuate through main exits	None
Occupants panic when they notice rapidly accumulating smoke	None
Occupants evacuate through windows	No pedestrian agents evacuated through windows in the Rhode Island nightclub scenario.
Occupants find a place to hide	The number of deaths that occurred in a room in the Gothenburg dance hall model was relatively low compared to fire statistics.
Occupants search for alternative routes	The results that were calculated by two navigation algorithms showed a significant difference in the number of evacuees at the emergency exit of the Rhode Island nightclub scenario.
Occupants escape from the fire or smoke	Pedestrian agents evacuated through the emergency exit that was covered by fire/smoke agents in the Gothenburg dance hall scenario.

Table 7-14 The issues occurred when comparing the simulation results to fire statistics.

Evaluating Method	Issues
Number of deaths and injuries	Modelling issues that were identified above might influence the results of the number of deaths and injuries.
Distribution of deaths	The distribution of deaths in the Gothenburg dance hall model was significantly different to the fire statistics and between the two navigation algorithms. The model simulated that only a few deaths occurred in the Dart room and the storage area, where many people died in the actual Rhode Island nightclub fire disaster.

According to the results from the evaluation of the preliminary model, the model was modified and improved for further main tests (Chapter 8). In addition, the number of multiple simulation runs required in order to produce significant results for statistical analysis was calculated by a sample size determination and defined. The model decided on 400 runs for the Gothenburg dance hall scenario, and 500 runs for both the Rhode Island nightclub and the Hamlet chicken processing plant scenarios.

8. Main Simulation Outcomes

Introduction and Background	Contents of Evacuation Modelling	Developing Research Questions	Developing an Evacuation Model	Simulation Outcomes	Discussion	Conclusion and Further Work
Ch. 1	Ch. 2	Ch. 3	Ch. 4, 5 and 6	Ch. 7, 8 and 9	Ch. 10	Ch. 11

8.1 Introduction

The previous chapter evaluated the preliminary model by examining human behaviour and victims in the scenarios of the Gothenburg dance hall fire and the Rhode Island nightclub fire. After modification and improvement of the model, further tests are used to validate the simulation results. In addition to the two nightclub fire scenarios, an additional industry scenario, the Hamlet chicken processing plant fire, was built to validate the results in a different type of building.

This chapter explores the simulation outcomes by applying five main tests, including egress selection, the evacuation time, the number of deaths and injuries, the number and distribution of deaths and the system run time. These tests are designed to validate the model in terms of the criteria for evacuation modelling identified in Section 3.5. Therefore, the simulation results that were output for the validation are displayed or compared to the fire statistics, if applicable, in this chapter, and an overall view of the model usage is discussed in Chapter 10. Individual results are presented first, and all results are summarised at the end of the chapter.

8.2 Main Tests

In order to identify whether the model is suitable for prediction or realisation purposes of applications, three criteria for validating the evacuation model are used, including realism, accuracy and processing speed (Section 3.5).

Firstly, the realism of the model is validated by egress selection (Section 8.2.1), which shows how people evacuate the building in fire disasters. In addition, evacuation time is calculated in the model to identify the safe evacuation period during which people can escape from the fire. However, the accurate evacuation time was not recorded in any fire report, so the simulation results are displayed to show the potential safe evacuation time in the buildings (Section 8.2.2). Next, the accuracy of the model is validated by risk area identification, including the number of deaths and injuries (Section 8.2.3) and the distribution of deaths (Section 8.2.4). Finally, processing speed is validated by the system run times displayed in Section 8.2.5.

The following subsections display the results of the five main tests on three fire evacuation scenarios using the 0.5 m^2 grid-based model: the Gothenburg dance hall fire, the Rhode Island nightclub fire and the Hamlet chicken processing plant fire. The results of the 0.5 m^2 grid-based model are compared to the smaller grid size (0.3 m^2) model in Section 9.2. The number of simulation runs of each scenario was based on the decisions made in Section 7.3.2. The simulation results are compared to the fire report statistics if applicable in order to identify how accurately the model represents pedestrian evacuation in real-life fire disasters. In addition, a non-parametric statistical hypothesis test, the Wilcoxon signed ranks test, is used to compare simulation results of the two navigation algorithms.

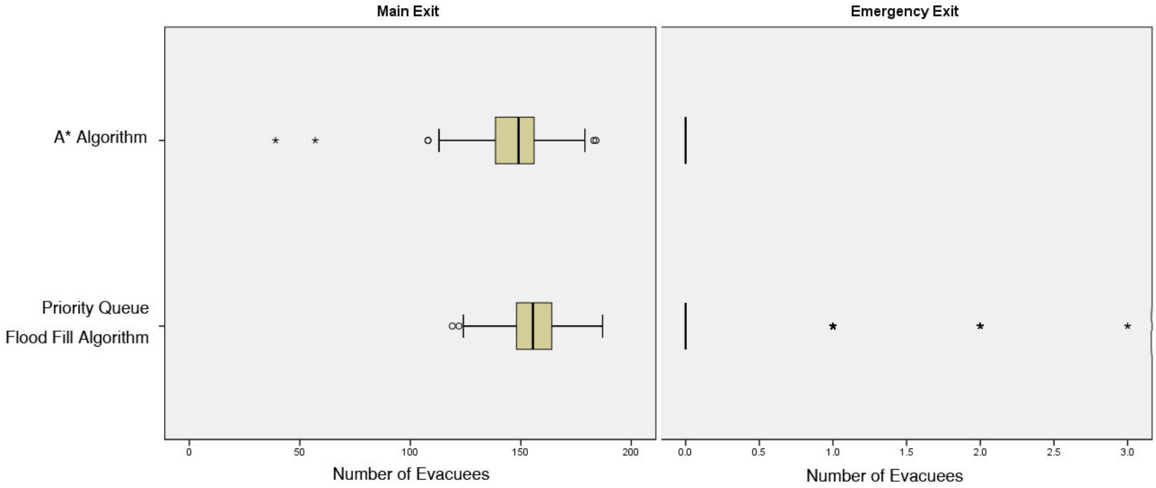
8.2.1 Test 1: Egress Selection

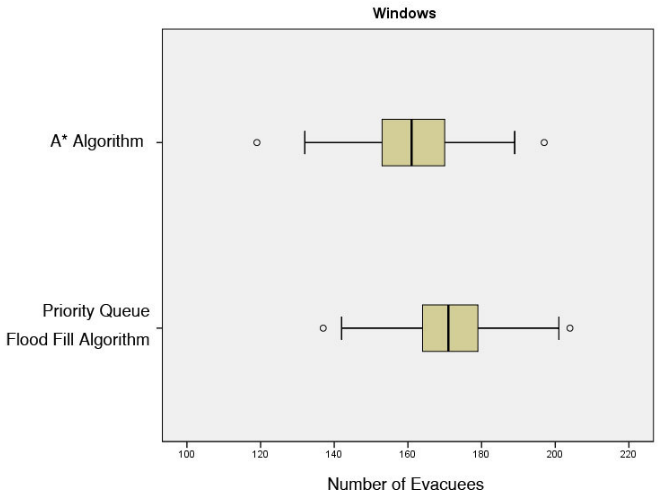
The first main test was developed to understand how occupants select an exit through which to evacuate from the fire. The studied fire reports show that occupants had several egress choices in each building. In addition to the main doors that were in daily use and emergency exits that were designed for specific situations, windows were another option for evacuation in lower-floor buildings.

However, since the actual numbers of evacuees at exits or windows were not recorded during the disasters, there was a lack of information with which to validate the realism of evacuation modelling. Of the collected fire reports, only the Rhode Island nightclub fire report recorded the numbers of evacuees in the fire disaster. Therefore, the realism of the model is validated by the results of the Rhode Island nightclub scenario, and other results are displayed to show potential evacuation movement in the buildings.

Case 1: Gothenburg Dance Hall

Figure 8-1 show the overall numbers of pedestrian agents who evacuated through the windows and the exits located at each end of the Gothenburg dance hall (see Figure 6-16). In addition, the statistical tests show that the results of egress selections are presented differently by the two navigation algorithms. According to the results, windows and the main exit are used by most of the evacuees, and none of them evacuated through the emergency exit where the fire originally started. Although the fire report described that people used the main exit and windows to escape the building due to one available exit (Section 6.4.1), the simulation results cannot compared to the incident as no statistics are provided in the fire report.





	Wilcoxon Signed Ranks Test on Algorithms
Main Exit	Rejected
Emergency Exit	Rejected
Windows	Rejected

Figure 8-1 Number of evacuees at different egress routes using different navigation algorithms in the Gothenburg dance hall scenario and statistical tests of the two navigation algorithms

Case 2: Rhode Island Nightclub

A total of four exits and windows were available in the Rhode Island nightclub (see Figure 6-18). Among the four exits, the front entrance, the main bar side exit and the platform exit were mainly used for evacuation in the actual Rhode Island nightclub fire disaster (Section 6.4.2). Another exit that was located in the kitchen was blocked in the model, because the kitchen area was not available to the public during the actual fire evacuation. Section 9.3 displays the results of additional modelling tests that were simulated with access to the kitchen area and the kitchen exit.

Figure 8-2 shows the number of pedestrian agents who evacuated through different egress routes and Table 8-1 displays the percentages of similarities between the simulation results and the fire report statistics and the statistical tests of the two navigation algorithms. The numbers of pedestrian agents who evacuated through the front entrance and windows are over 75% of similarities when comparing to actual fire statistics. In contrast, the main bar side exit was used by the least number of pedestrian agents in the simulations, resulting low similarities (<20%) when comparing to the actual statistics. The results of Wilcoxon sign ranks tests show both navigation algorithms calculated similar results on the number of evacuees who used windows as an egress route.

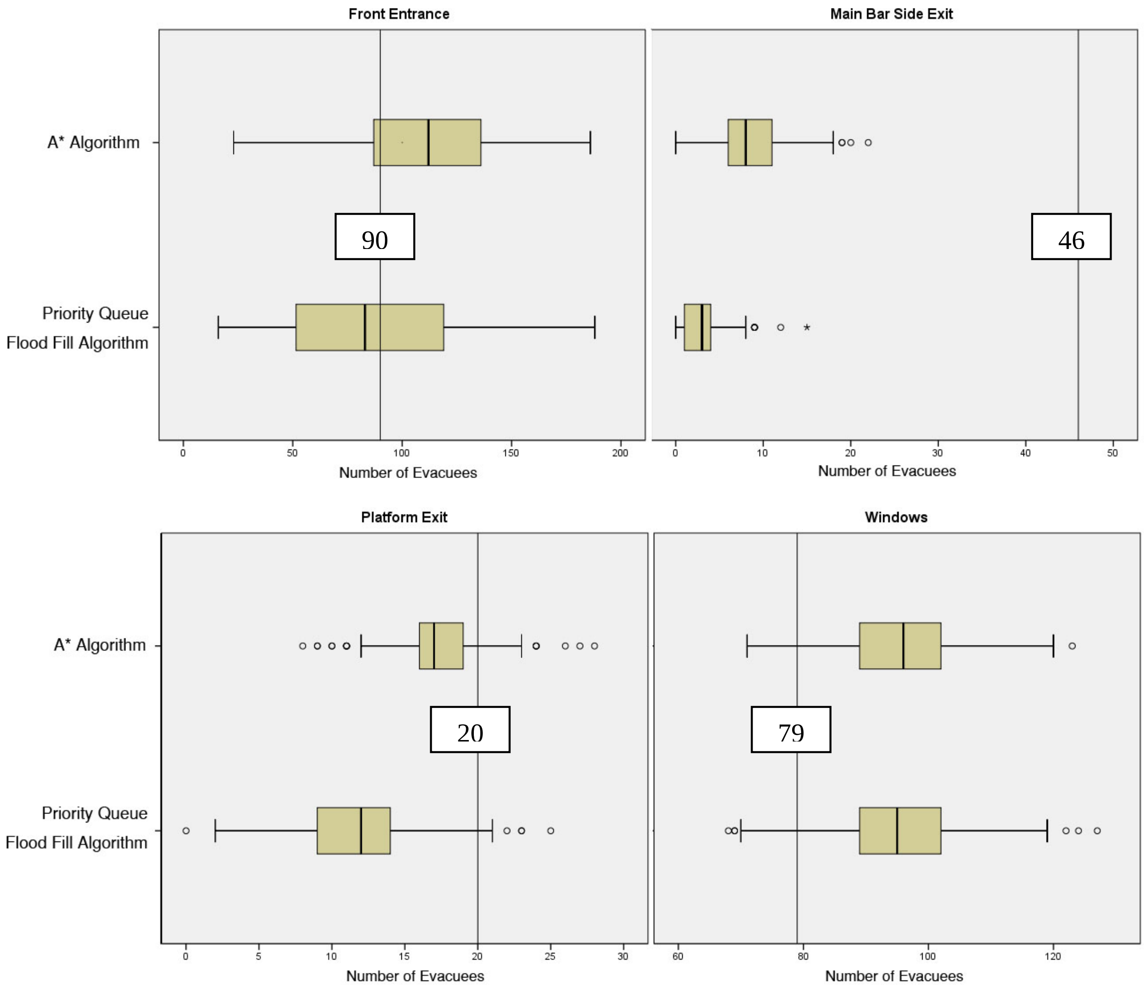


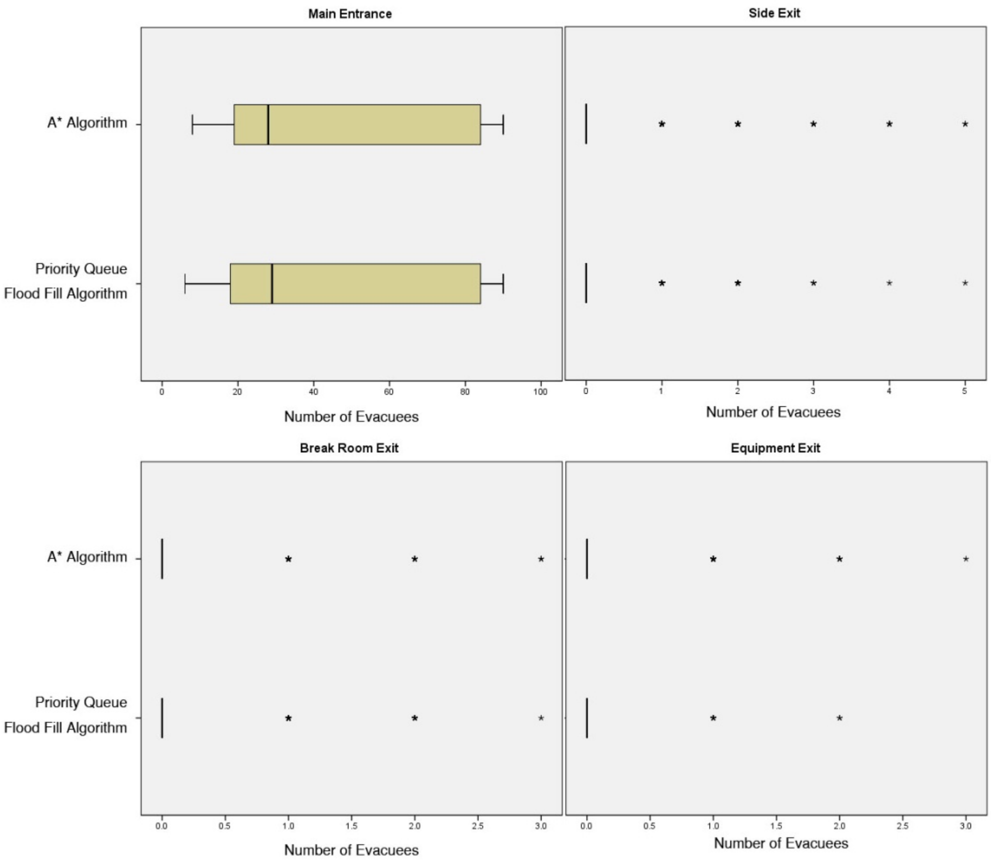
Figure 8-2 Number of evacuees at different egress routes using different navigation algorithms in the Rhode Island nightclub scenario (vertical lines: fire report statistics)

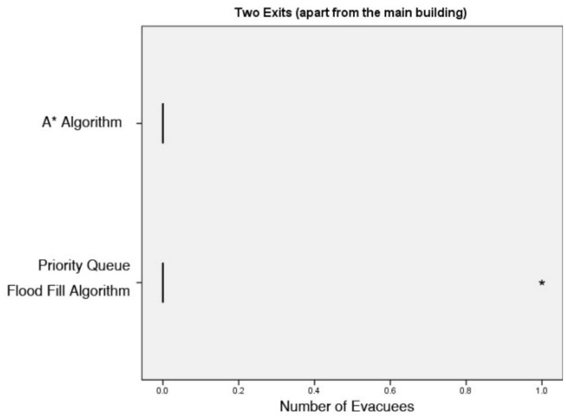
Table 8-1 Similarities of fire report statistics and the number of evacuees (median value of 500 runs) in the Rhode Island nightclub scenario and statistical tests of the two navigation algorithms

	Front Entrance	**Main Bar Side Exit**	**Platform Exit**	**Windows**
A* Algorithm	75.6%	17.4%	85.0%	78.5%
Priority Queue Flood Fill Algorithm	92.2%	6.5%	60.0%	79.7%
Wilcoxon Signed Ranks Test on Algorithms	Rejected	Rejected	Rejected	Accepted

Case 3: Hamlet Chicken Processing Plant

Seven external exits and no windows were available in the Hamlet chicken processing plant, as displayed in Figure 6-22. The model blocked one of the exits in the equipment room in terms of the information in the figure, which shows the door was locked and not opened during the evacuation. Figure 8-3 shows the numbers of people who evacuated through the rest of the six exits and statistical tests of the two navigation algorithms. Almost all of the evacuees passed through the main entrance instead of other exits, but no fire statistics are available to identify the similarities in this case. The visual patterns and the Wilcoxon signed ranks tests show high similarities of the results between two navigation algorithms at every exit except the equipment exit.





	Wilcoxon Signed Ranks Test on Algorithms
Main Entrance	Accepted
Side Exit	Accepted
Break Room Exit	Accepted
Equipment Exit	Rejected
Two Exits (apart from the main building)	Accepted

Figure 8-3 Number of evacuees at different egress routes using different navigation algorithms in the Hamlet chicken processing plant scenario and statistical tests of the two navigation algorithms

8.2.2 Test 2: Evacuation Time

Evacuation time is one of the criteria for validating evacuation models, but no statistics of actual evacuation times were recorded in any fire report. Therefore, the simulation results in this section are displayed present a potential safe evacuation time rather than calculate its accuracy in these three fire cases. The displayed overall evacuation time is defined as the time of the last evacuee who passed through each exit.

The following figures show the evacuation time spent at each exit or windows in the Gothenburg dance hall scenario (Figure 8-4), the Rhode Island nightclub scenario (Figure 8-5) and the Hamlet chicken processing plant scenario (Figure 8-6). Although no statistics were recorded in the fire reports, an observation timeline of the fire was displayed in the Rhode Island nightclub fire report (Figure 6-19), showing that "people piled up in the doorway" at 01:42 and "occupants still being assisted through main bar windows" at 04:08. In other words, in the actual disaster, occupants had difficulty evacuating through the front entrance after 102 seconds, and people were still evacuating through windows at 248 seconds. Therefore, the simulation results were about ±2 minutes adrift compared to actual events in the Rhode Island nightclub fire.

Table 8-2 Summary of the evacuation time (median value) at exit or windows in three scenarios and the statistical tests of the two navigation algorithms

Scenario	Egress Selection	Evacuation Time[1]		Wilcoxon Signed Ranks Test on Algorithms
		A*	PF	
Gothenburg Dance Hall	Main Exit	273 sec	258 sec	Rejected
	Emergency Exit	0 sec	0 sec	Rejected
	Windows	239 sec	214 sec	Rejected
Rhode Island Nightclub	Front Entrance	237 sec	189 sec	Rejected
	Main Bar Side Exit	64 sec	51 sec	Rejected
	Platform Exit	44 sec	42 sec	Rejected
	Windows	184 sec	187 sec	Accepted
Hamlet Chicken Processing Plant	Main Entrance	156 sec	144 sec	Accepted
	Side Exit	0 sec	0 sec	Accepted
	Break Room Exit	0 sec	0 sec	Accepted
	Equipment Exit	0 sec	0 sec	Rejected
	Two Exits (apart from the main building)	0 sec	0 sec	Accepted

[1]A*: A* algorithm; PF: Priority Queue Flood Fill algorithm

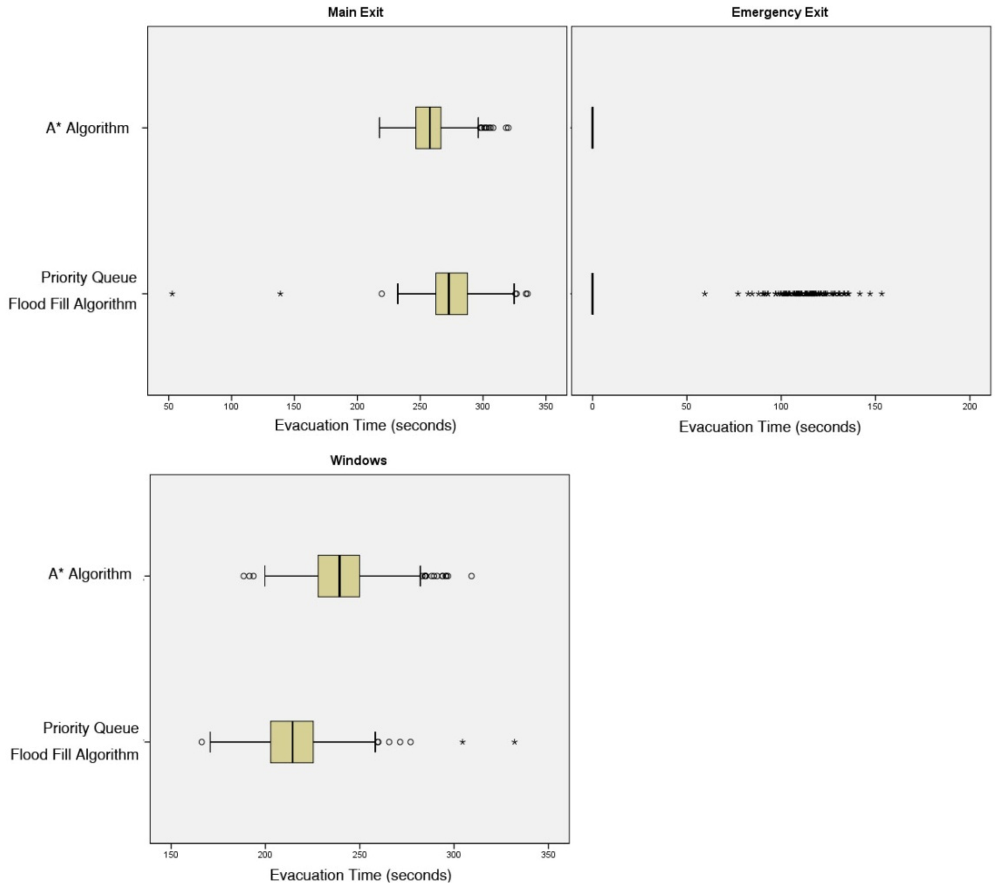


Figure 8-4 Evacuation time at each exit or windows using different navigation algorithms in the Gothenburg dance hall scenario

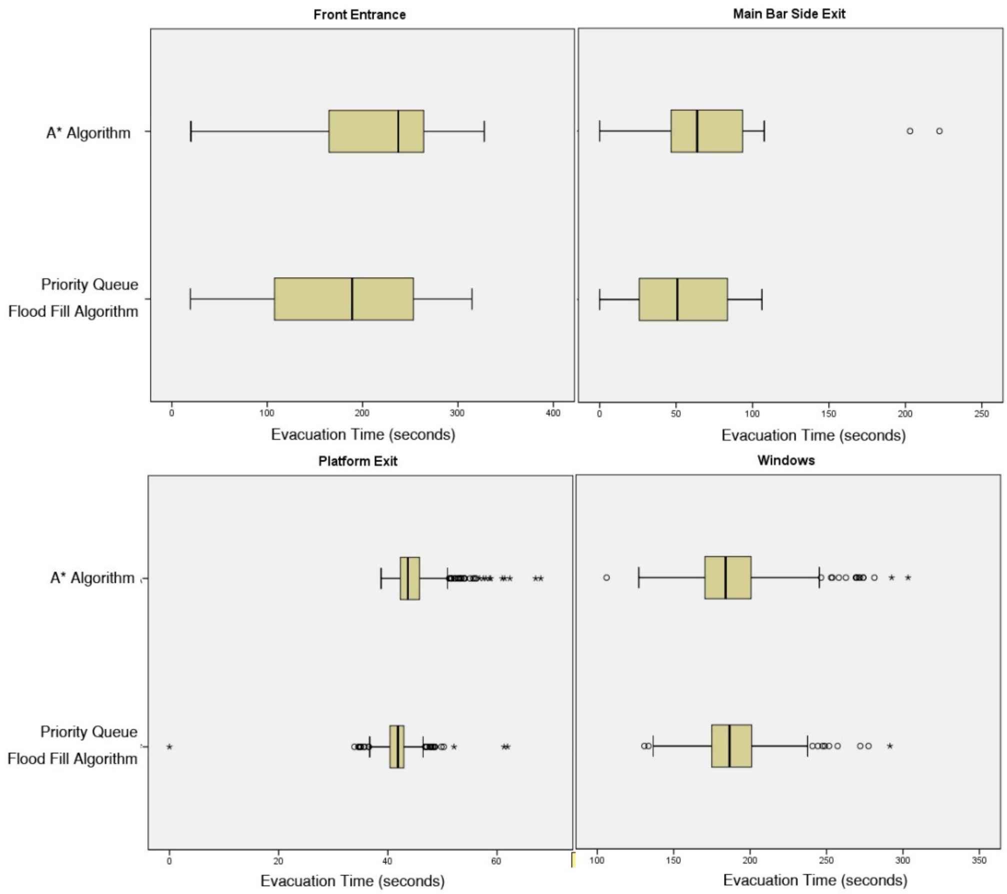


Figure 8-5 Evacuation time at each exit or windows using different navigation algorithms in the Rhode Island nightclub scenario

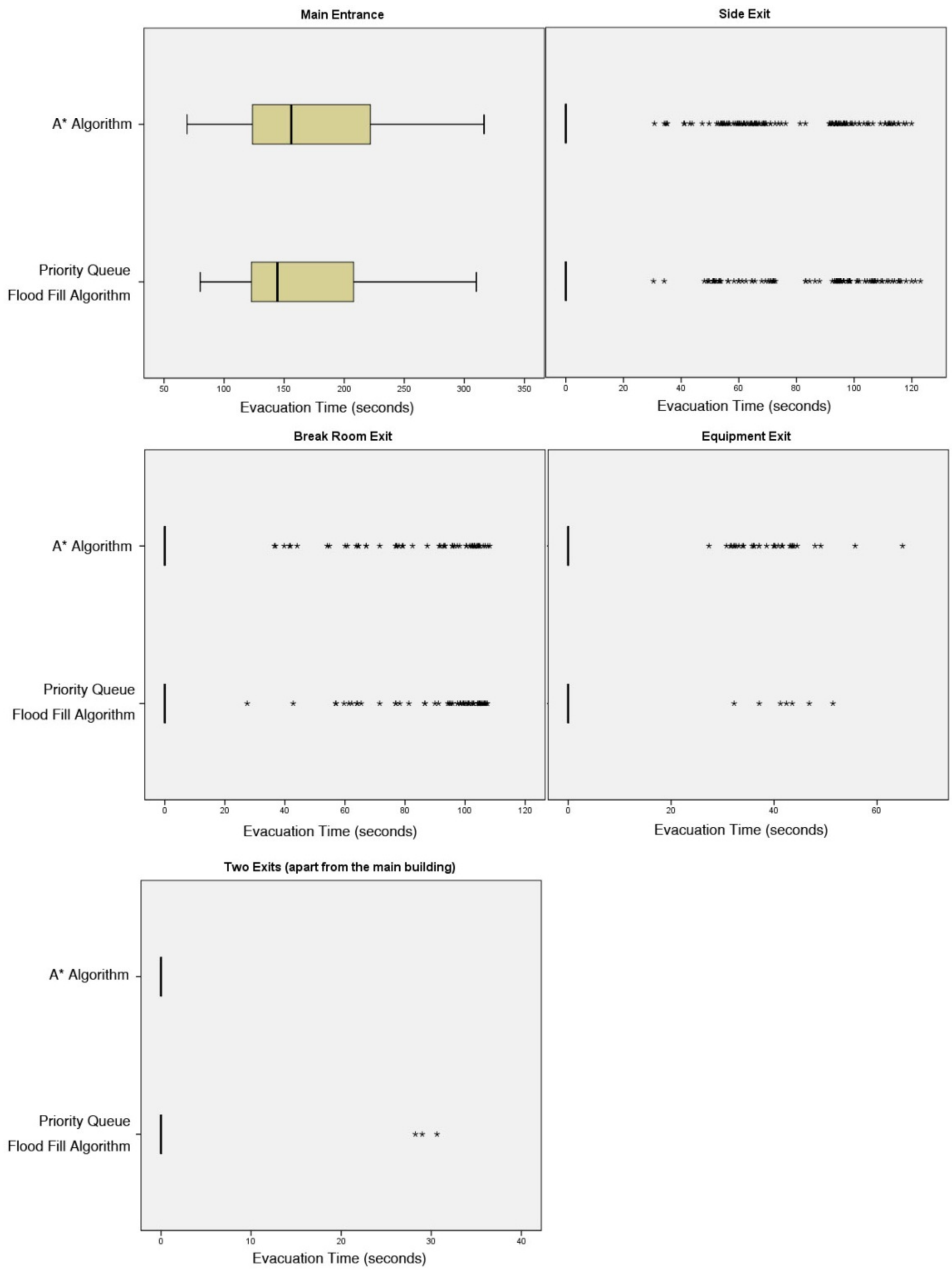


Figure 8-6 Evacuation time at each exit or windows using different navigation algorithms in the Hamlet chicken processing plant scenario

Based on the results, a potential safe evacuation time for future evacuation plans in the same building or structures with a similar configuration can be identified. For example, occupants might have 258-273 seconds (about 4.5 minutes) to exit the Gothenburg dance hall, 189-237 seconds (less than 4 minutes) to escape the Rhode Island nightclub and 144-156 seconds (about 2.5 minutes) to evacuate successfully from the Hamlet chicken processing plant.

8.2.3 Test 3: Numbers of Deaths and Injuries

The accuracy of the model is validated by risk area identification, including the number of deaths and injuries and the distribution of deaths (Section 8.2.4). In the following cases, the numbers of deaths and injuries in each fire evacuation scenario are presented and compared to the statistics in the fire reports.

Case 1: Gothenburg Dance Hall

Figure 8-7 shows the numbers of deaths and injuries in the Gothenburg dance hall scenario, and these values are further compared to the fire report statistics followed by a statistical test for examining the results of the two navigation algorithms (Table 8-3). The value that was calculated by the Priority Queue Flood Fill algorithm is further from the actual fire statistics, which the percentage of similarity is 14.3% less than the A* algorithm. In addition, the results of the Wilcoxon signed ranks test show that the two algorithms calculated different results of the number of deaths but the same results of the number of injuries. Overall, the model simulated a higher similarity of the number of injuries when comparing to the fire report statistics.

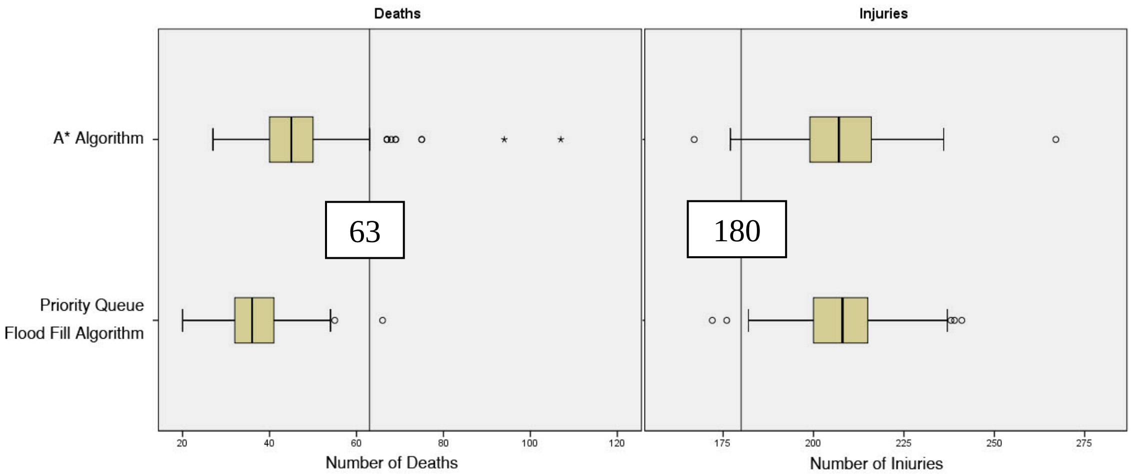


Figure 8-7 Number of deaths and injuries using different navigation algorithms in the Gothenburg dance hall scenario (vertical lines: fire report statistics)

Table 8-3 Similarities of fire report statistics and the number of victims (median value of 400 runs) in the Gothenburg dance hall scenario and statistical tests of the two navigation algorithms

	Deaths	**Injuries**
A* Algorithm	71.4%	85.0%
Priority Queue Flood Fill Algorithm	57.1%	84.4%
Wilcoxon Signed Ranks Test on Algorithms	Rejected	Accepted

Case 2: Rhode Island Nightclub

Figure 8-8 shows the simulation results of the number of deaths and injuries in the Rhode Island nightclub scenario. Both the numbers of deaths and injuries are calculated differently by the two navigation algorithms according to the Wilcoxon signed ranks test (Table 8-4). The Priority Queue Flood Fill algorithm calculated 20 pedestrian agents more in both of the results when comparing the median values of the two algorithms. In terms of the similarities, the numbers of deaths, which are 75.3% (A* algorithm) and 52.8% (Priority Queue Flood Fill algorithm), present less close to the actual statistics as compared to the number of injuries (over 90%).

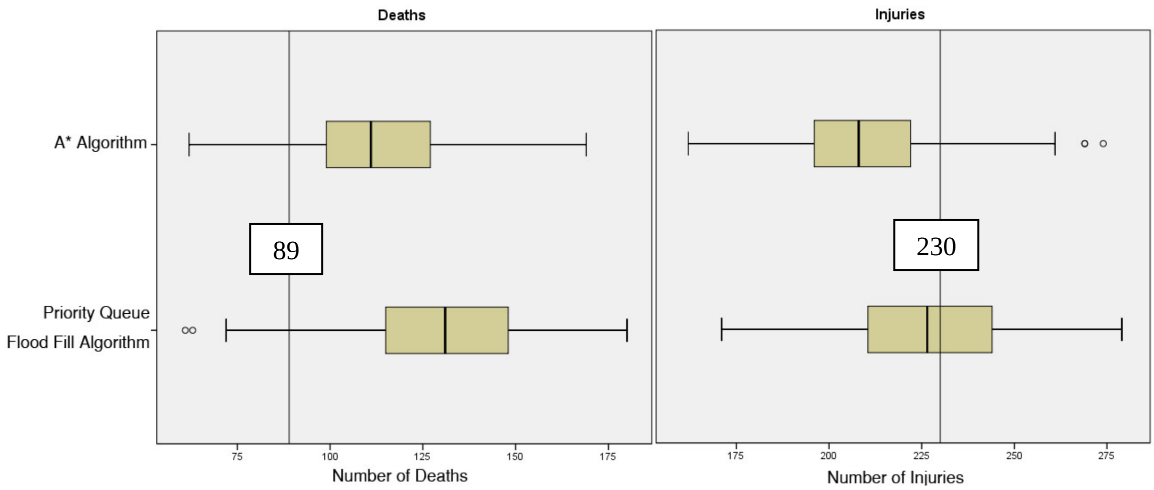


Figure 8-8 Number of deaths and injuries using different navigation algorithms in the Rhode Island nightclub scenario (vertical lines: fire report statistics)

Table 8-4 Similarities of fire report statistics and the number of victims (median value of 500 runs) in the Rhode Island nightclub scenario and statistical tests of the two navigation algorithms

	Deaths	**Injuries**
A* Algorithm	75.3%	90.4%
Priority Queue Flood Fill Algorithm	52.8%	98.7%
Wilcoxon Signed Ranks Test on Algorithms	Rejected	Rejected

Case 3: Hamlet Chicken Processing Plant

Figure 8-9 shows the numbers of deaths and injuries in the Hamlet chicken processing plant scenario. The simulation results are compared to the fire report statistics, and statistical tests are conducted to examine the two navigation algorithms (Table 8-5). According to the table, the similarities of the number of deaths are higher than the number of injuries, and the Priority Queue Flood Fill algorithm calculated slightly better. However, both navigation algorithms output similar numbers of deaths and injuries.

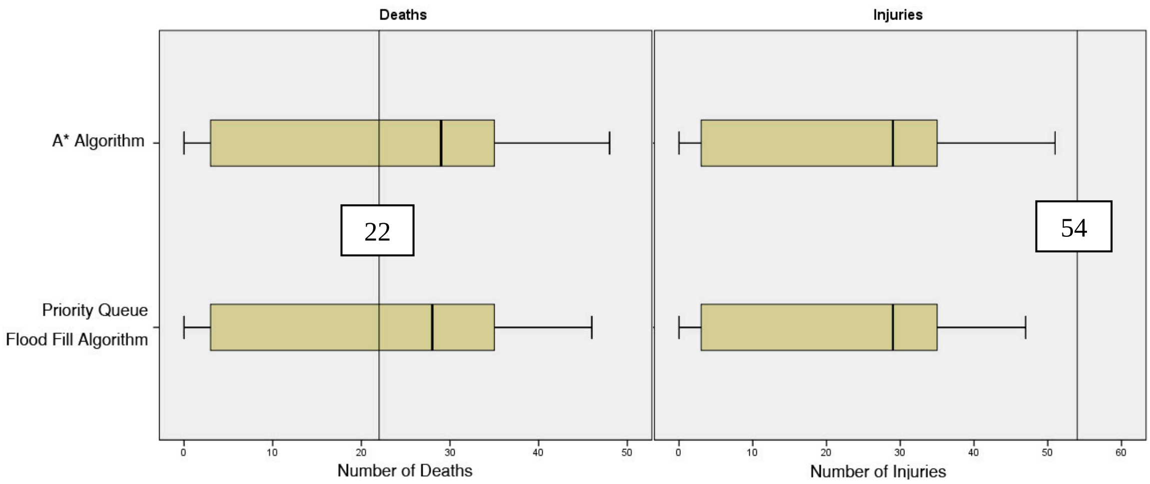


Figure 8-9 Number of deaths and injuries using different navigation algorithms in the Hamlet chicken processing plant scenario (vertical lines: fire report statistics)

Table 8-5 Similarities of fire report statistics and the number of victims (median value of 500 runs) in the Hamlet chicken processing plant scenario and statistical tests of the two navigation algorithms

	Deaths	**Injuries**
A* Algorithm	68.2%	53.7%
Priority Queue Flood Fill Algorithm	72.7%	53.7%
Wilcoxon Signed Ranks Test on Algorithms	Accepted	Accepted

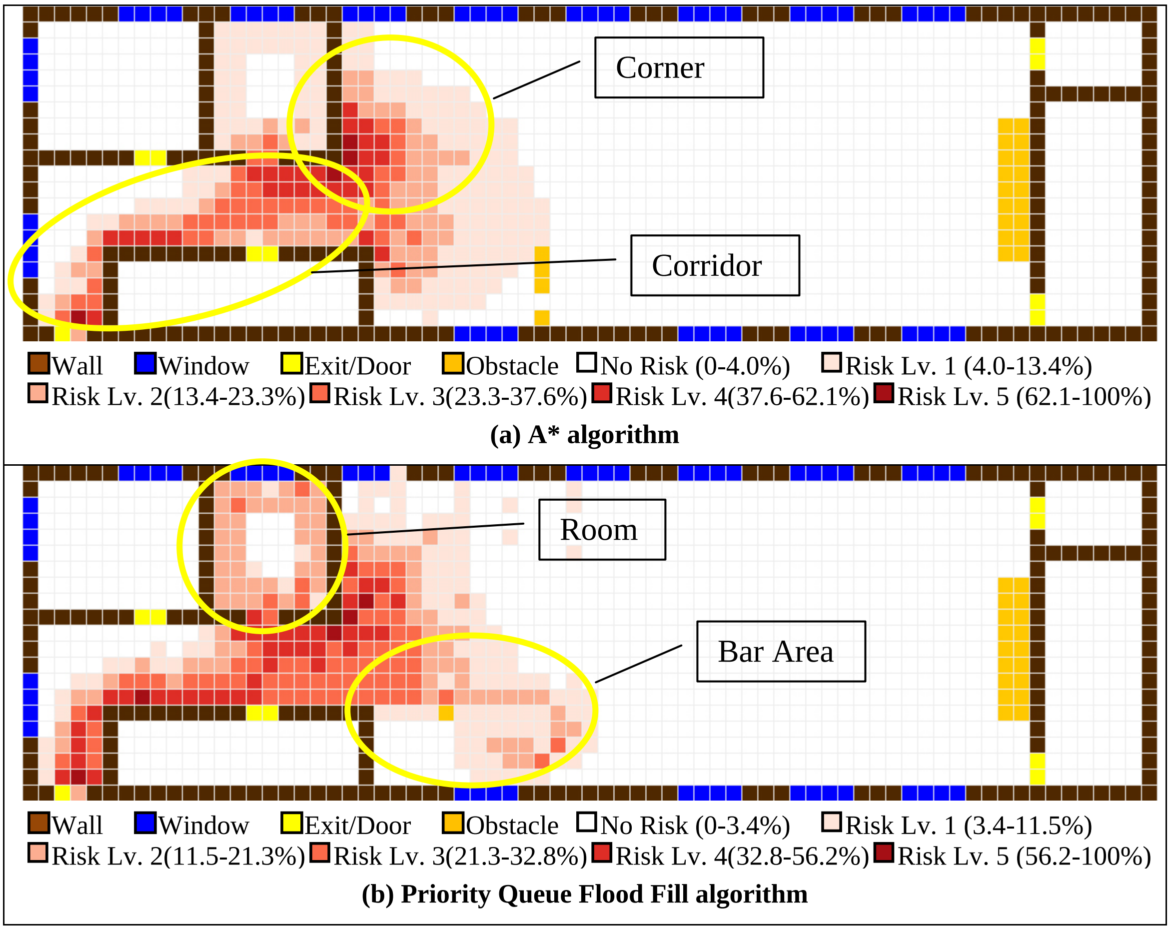
8.2.4 Test 4: Distribution of Deaths

In addition to the previous test, another test to validate the accuracy of the model is the distribution of deaths. To display the distribution of deaths, casualties were plotted on a grid-based choropleth map. As mentioned in Section 7.2.2, choropleth maps present six risk levels using Natural Break classification. Red cells represent different numbers of deaths that occurred in the total simulation runs, and white cells indicate that no or few deaths occurred during the simulations. Next, the space was divided into regions in terms of the highlighted areas in which a greater number of deaths occurred, identified by the choropleth map and the fire report.

Following that, the results of deaths in each area are presented in two ways: the number of deaths and the percentage of deaths that occurred in an area. The percentage of deaths was calculated to show the potential occurrence of death in a specific area, because the total numbers of deaths in the simulations that differ from the fire statistics might not be accurately represented in terms of risk area identification. Therefore, both results are compared to the statistics from the fire reports.

Case 1: Gothenburg Dance Hall

The distribution of deaths in the Gothenburg dance hall scenario is displayed in Figure 8-10. The cells that contain colours represent a level of risk in terms of the number of deaths over the simulation runs. According to the choropleth maps, a significant number of deaths occurred along the corridor and at the corner of the dance hall and the corridor. Therefore, these two areas are identified as high-risk areas (risk level 4 and 5) and the areas comprising the room and the bar are designated as mid-risk areas (risk level 2 and 3).



(a) A* algorithm

(b) Priority Queue Flood Fill algorithm

Figure 8-10 The potential death locations in the Gothenburg dance hall fire scenario

The fire report mentioned that deaths mainly occurred in the corridor and the room (Section 6.4.1), but the location of deaths was not recorded on a floor map. Although information regarding the death location was found (Cassuto and Tarnow, 2003), this thesis uses fire report statistics to validate the simulation results. Therefore, the grid-based Gothenburg dance hall space grouped cells into four regions according to the distribution of deaths on the choropleth map and the description in the fire report (Figure 8-11). The regions comprise the corridor (Region 1), the room (Region 2), the corner of the dance hall and the corridor (Region 3) and the bar area (Region 4).

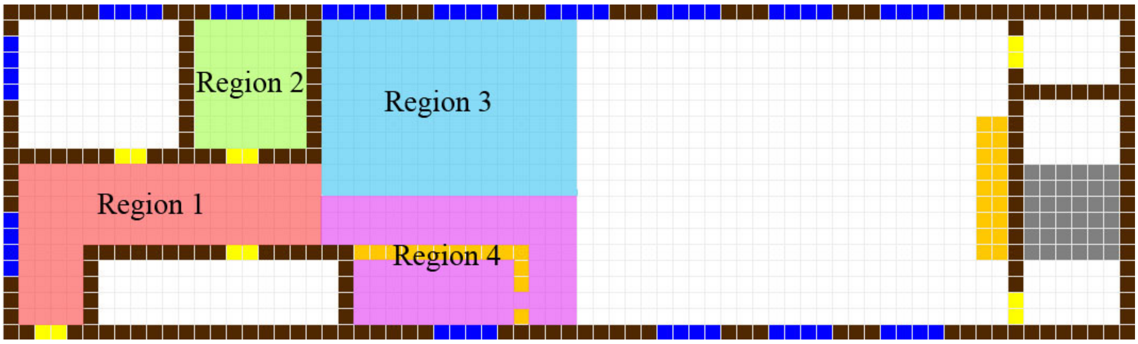


Figure 8-11 Region identification based on the distribution of deaths displayed on choropleth maps and the information in the Gothenburg dance hall fire report

Figure 8-12 shows the number of deaths by region in the Gothenburg dance hall scenario. The results show the number of deaths that occurred in the corridor and the room are far smaller than the actual statistics, resulting low percentages of similarities (Table 8-6). In particular, the model simulated that a large number of pedestrian agents died in the corner and the bar area (Region 3 and 4), where no victims perished in the actual fire disaster.

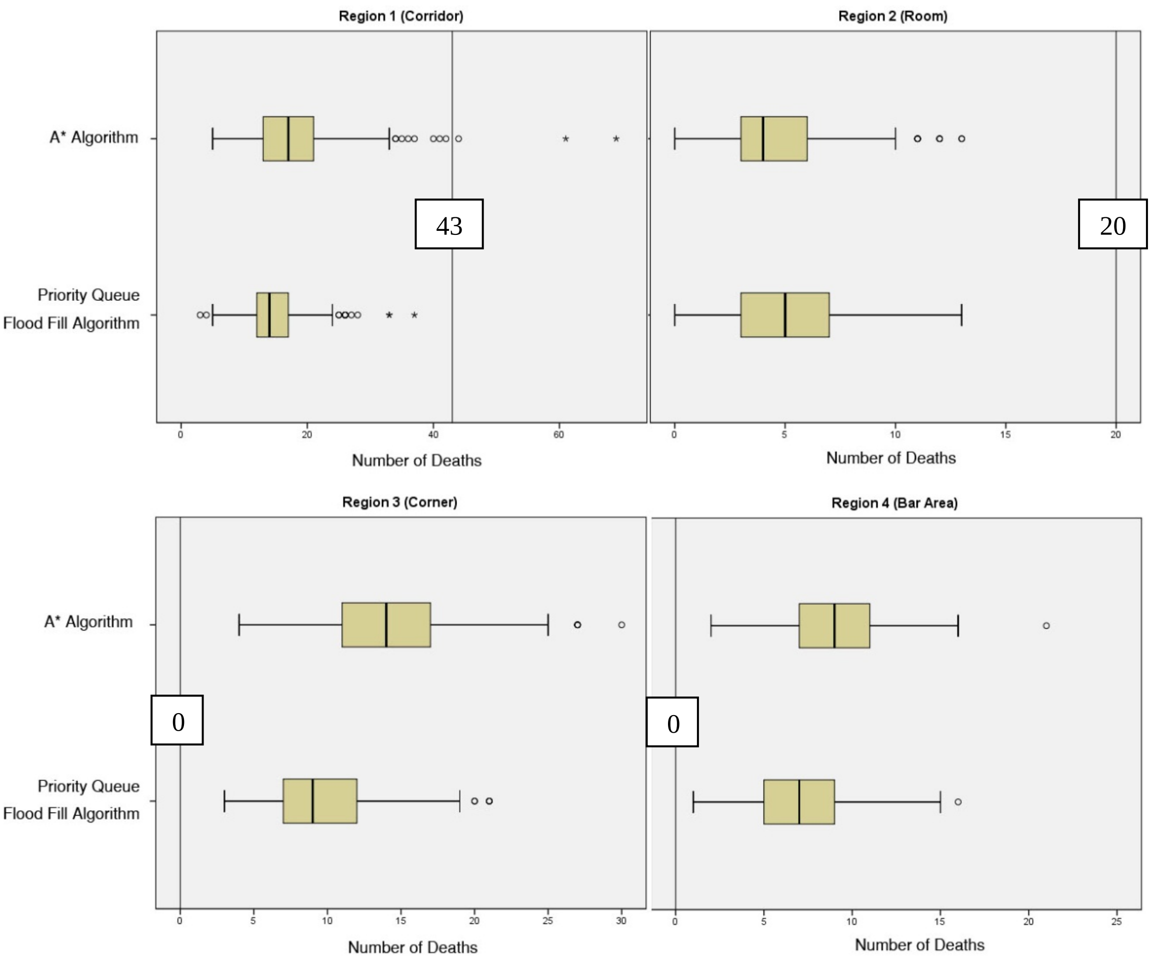


Figure 8-12 Numbers of deaths that occurred in regions 1 to 4 (see Figure 8-11) using different navigation algorithms in the Gothenburg dance hall scenario (vertical lines: fire report statistics)

Table 8-6 Similarities of fire report statistics and the number of deaths by region (median value of 400 runs) in the Gothenburg dance hall scenario and statistical tests of the two navigation algorithms

	Region 1 (Corridor)	**Region 2 (Room)**	**Region 3 (Corner)**	**Region 4 (Bar Area)**
A* Algorithm	39.5%	20.0%	0%	0%
Priority Queue Flood Fill Algorithm	32.6%	25.0%	0%	0%
Wilcoxon Signed Ranks Test on Algorithms	Rejected	Rejected	Rejected	Rejected

In addition to the number of deaths, the occurrence of deaths, which is calculated by the dividing the number of pedestrian agents who died in the corridor by the total number of deaths in each simulation run, shows the percentage of deaths that might occur in an area. In the actual fire disaster, deaths mainly occurred in the corridor (68.3%) and the room (31.7%). However, less than 40% of deaths occurred in the corridor and only about 10% of deaths in the room (Figure 8-13). Other deaths in simulations mainly occurred at the corner and bar area where no victim was recorded in the fire report. Therefore, the location of deaths was significantly different when the simulation results are compared to the fire statistics (Table 8-7). Finally, the statistical tests show that two navigation algorithms calculated similar percentages of deaths in region 1 (corridor) rather than similar numbers of deaths (see Table 8-6).

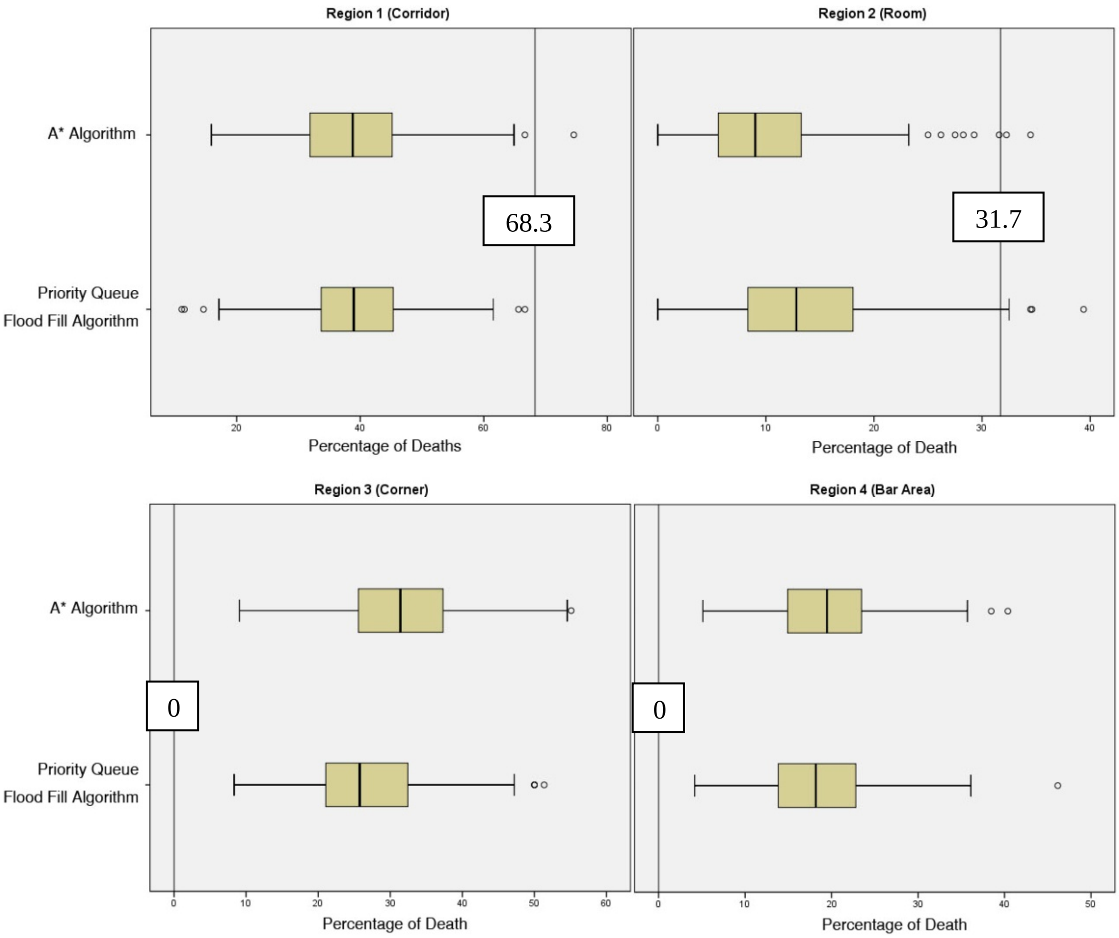


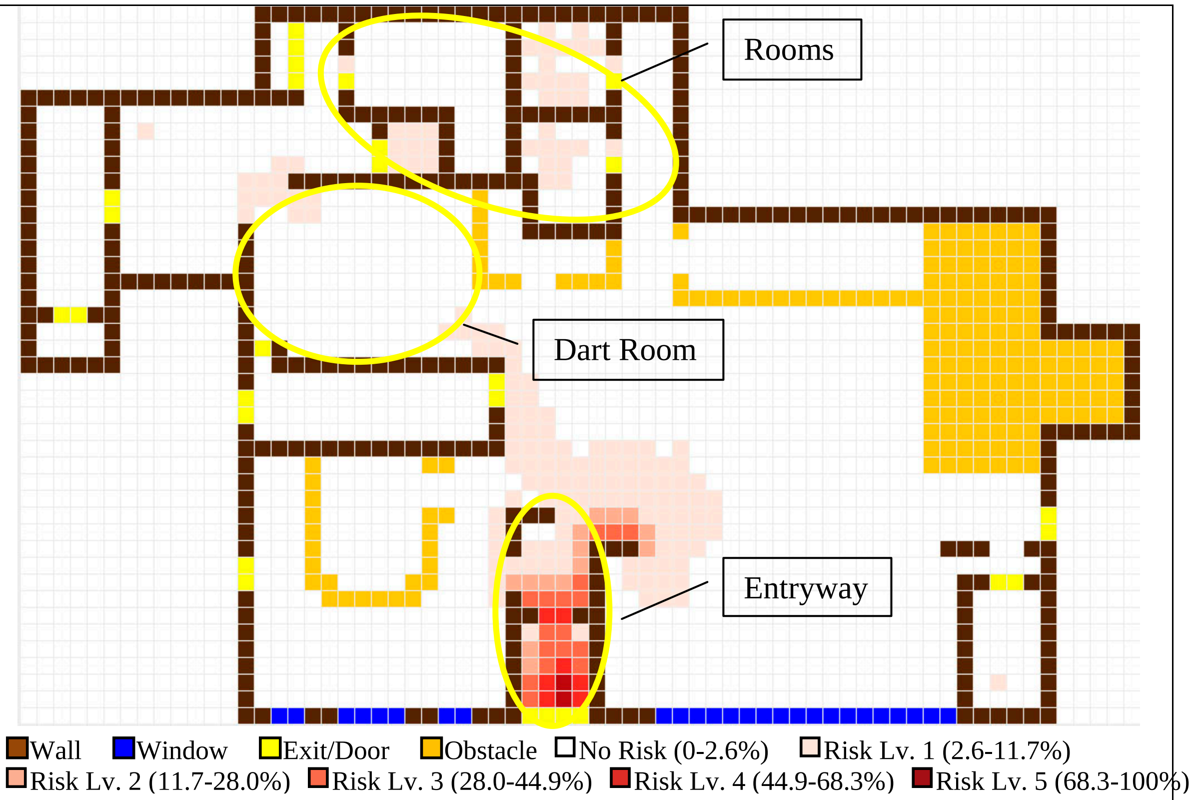
Figure 8-13 Percentage of deaths that occurred in region 1 to 4 using different navigation algorithms in the Gothenburg dance hall scenario (vertical lines: fire report statistics)

Table 8-7 Similarities of fire report statistics and the percentage of deaths by region (median value of 400 runs) in the Gothenburg dance hall scenario and statistical tests of the two navigation algorithms

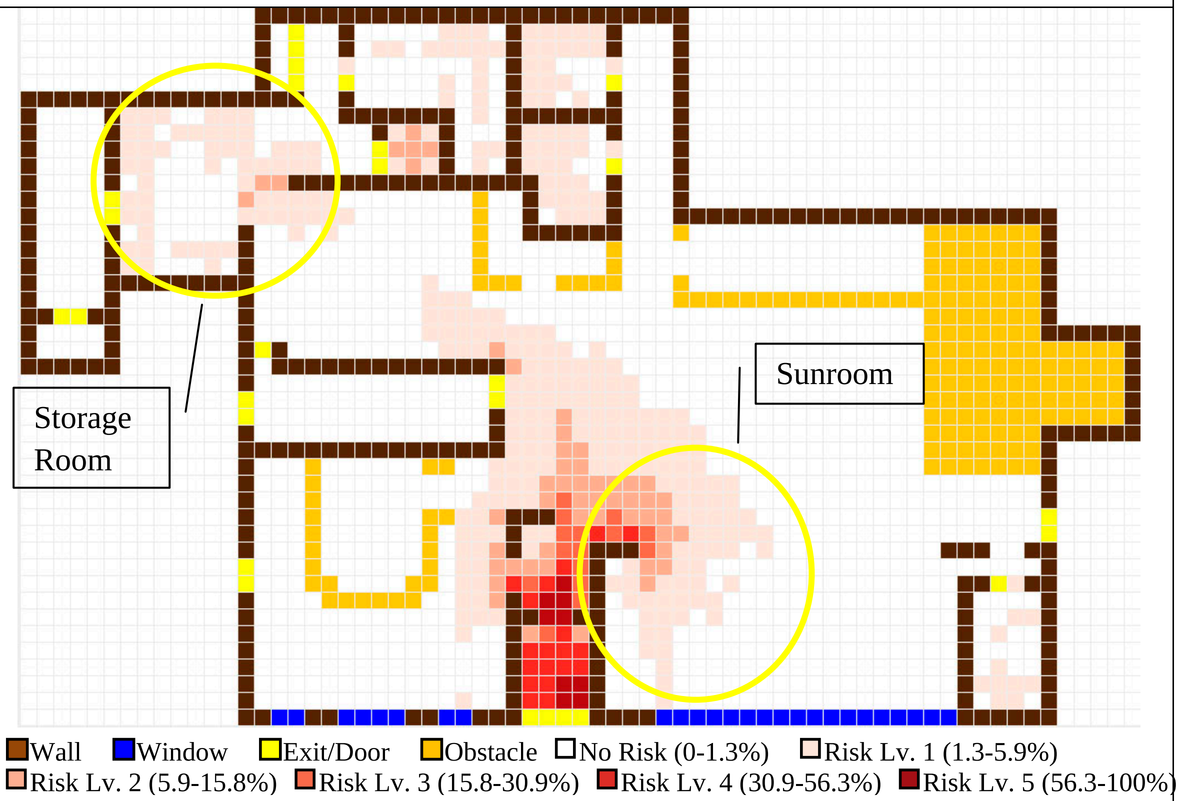
Navigation Algorithms	Region 1 (Corridor)	Region 2 (Room)	Region 3 (Corner)	Region 4 (Bar Area)
A* Algorithm	56.8%	28.3%	0%	0%
Priority Queue Flood Fill Algorithm	57.1%	40.4%	0%	0%
Wilcoxon Signed Ranks Test on Algorithms	Accepted	Rejected	Rejected	Rejected

Case 2: Rhode Island Nightclub

The distribution of deaths in the Rhode Island nightclub scenario is displayed on choropleth maps (Figure 8-14). Deaths mainly occurred along the corridor near the main entrance, which is thus identified as a high-risk area (risk level 4 and 5). The second area of risk, mid-risk level (risk level 2 and 3), was identified at the entrance to the route from the dance hall to the corridor, which was close to the Sunroom. Other areas were identified as low-risk areas due to few deaths occurring at these areas during the simulations.



(a) A* algorithm



(b) Priority Queue Flood Fill algorithm

Figure 8-14 The potential death locations in the Rhode Island nightclub scenario

According to the simulation outcomes (Figure 8-14) and the number of deaths grouped by location in the fire report (Figure 6-20), the places that contained many deaths were identified into regions. Therefore, the cells of the grid-based Rhode Island nightclub floor map were grouped into five regions (Figure 8-15): entryway (Region 1), rooms (Region 2), storage area (Region 3), the Dart room (Region 4), and the Sunroom (Region 5).

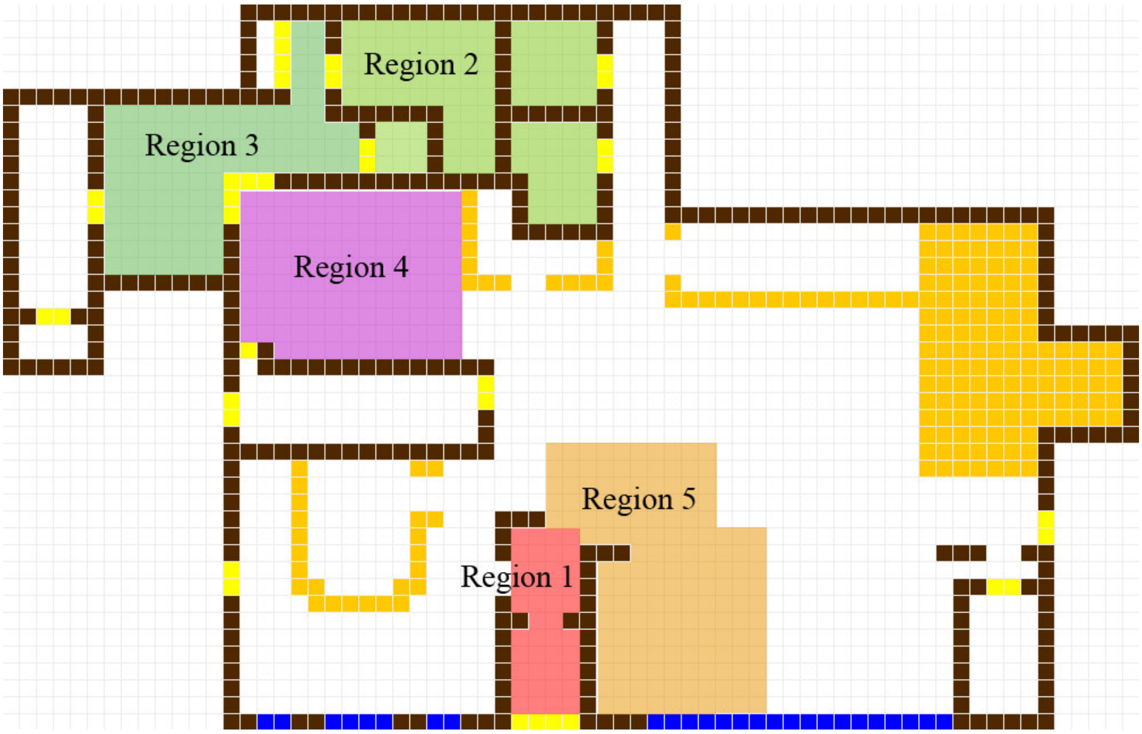


Figure 8-15 Region identification based on the distribution of deaths displayed on a choropleth map and the information in the Rhode Island nightclub fire report

Figure 8-16 displays the number of deaths that occurred in each region of the Rhode Island nightclub scenario. Table 8-8 shows low percentages of similarities in the entryway (Region 1) and the Dart room (Region 4). Firstly, the number of deaths in the entryway was calculated to be far greater than the number of deaths that occurred in the actual fire disaster. Secondly, the number of deaths in the Dart room was less than half of the number presented in the fire statistics. The numbers of deaths in the rooms (Region 2), the storage area (Region 4) and the Sunroom (Region 5) show a difference of less than five victims, so these regions were identified as having higher percentages of similarities.

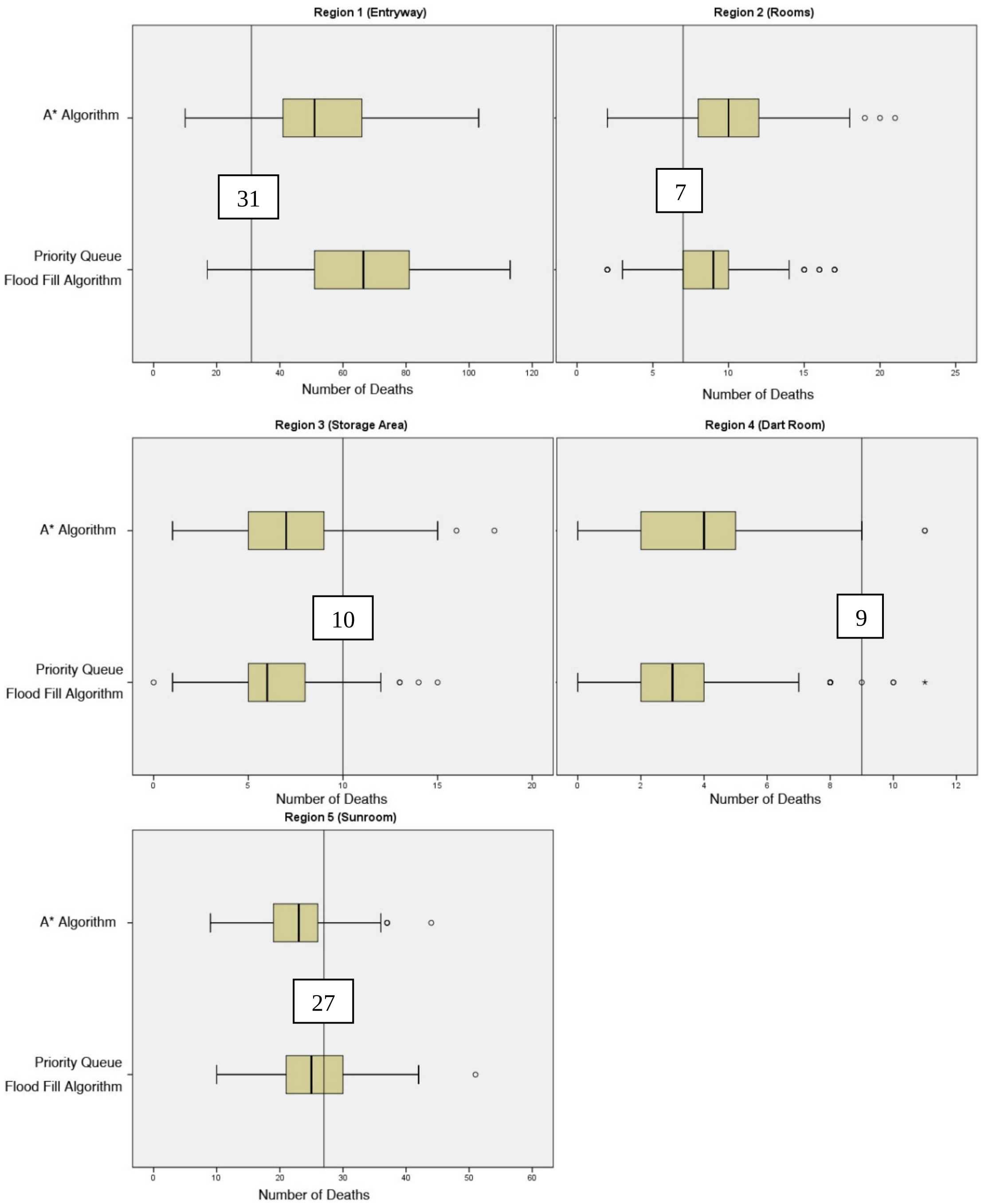


Figure 8-16 Number of deaths that occurred in region 1 to 5 (see Figure 8-15) using different navigation algorithms in the Rhode Island nightclub scenario (vertical lines: fire report statistics)

Table 8-8 Similarities of fire report statistics and the number of deaths by region (median value of 500 runs) in the Rhode Island nightclub scenario and statistical tests of the two navigation algorithms

	Region 1 (Entryway)	**Region 2 (Rooms)**	**Region 3 (Storage Area)**	**Region 4 (Dart Room)**	**Region 5 (Sunroom)**
A* Algorithm	35.5%	57.1%	70.0%	44.4%	85.2%
Priority Queue Flood Fill Algorithm	0%	71.4%	60.0%	33.3%	92.6%
Wilcoxon Signed Ranks Test on Algorithms	Rejected	Rejected	Rejected	Rejected	Rejected

The number of deaths presented as a percentage in each region shows how deaths were distributed over the space (Figure 8-17). Comparing the results in Table 8-8 and

Table 8-9, the percentages of similarities between the results and the statistics increased more than 30% in the entryway (Region 1) and the rooms (Region 2), especially the increase of 56.3% in the entryway that was calculated by the Priority Queue Flood Fill algorithm. In contrast, the similarities decreased by 10.5 to 28.6% in other areas when presenting the number of deaths as percentages. In addition, the statistical tests identified that two navigation algorithms produced similar percentages of deaths in the Sunroom (Region 4) while other outputs were different.

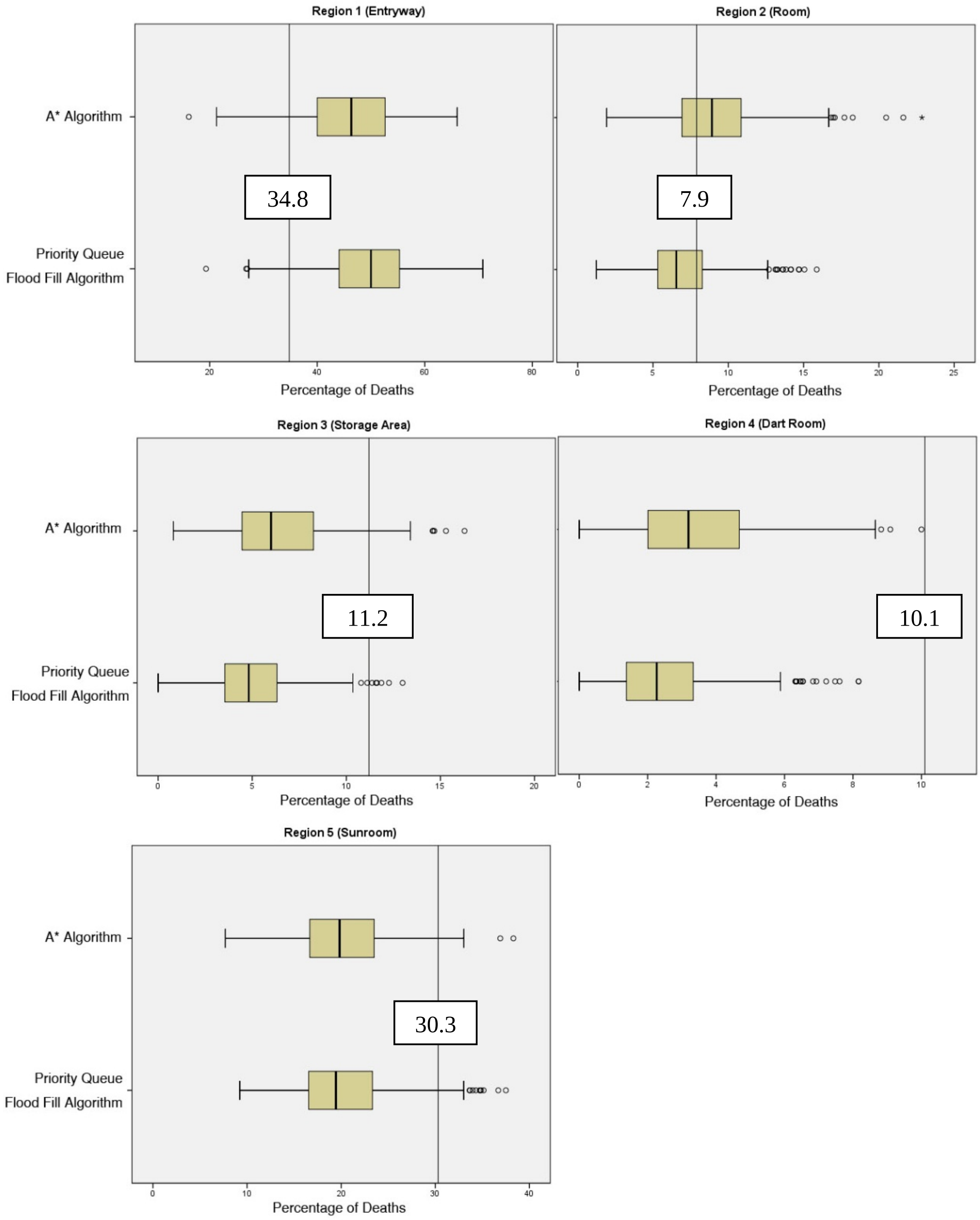


Figure 8-17 Percentage of deaths that occurred in region 1 to 5 using different navigation algorithms in the Rhode Island nightclub scenario (vertical lines: fire report statistics)

Table 8-9 Similarities of fire report statistics and the percentage of deaths by region (median value of 500 runs) in the Rhode Island nightclub scenario and statistical tests of the two navigation algorithms

Navigation Algorithms	**Region 1 (Entryway)**	**Region 2 (Rooms)**	**Region 3 (Storage Area)**	**Region 4 (Dart Room)**	**Region 5 (Sunroom)**
A* Algorithm	67.0%	87.3%	53.6%	31.7%	65.3%
Priority Queue Flood Fill Algorithm	56.3%	82.3%	42.9%	22.8%	64.0%
Wilcoxon Signed Ranks Test on Algorithms	Rejected	Rejected	Rejected	Rejected	Accepted

Case 3: Hamlet Chicken Processing Plant

The distribution of deaths in the Hamlet chicken processing plant scenario is displayed in Figure 8-18. According to the choropleth maps, almost all of the deaths occurred around the main entrance in the simulations. In reality, however, the fire report records two significant concentrations of deaths occurred in the cooler and the space adjacent to the origin of the fire (the processing room), as displayed in Figure 6-22.

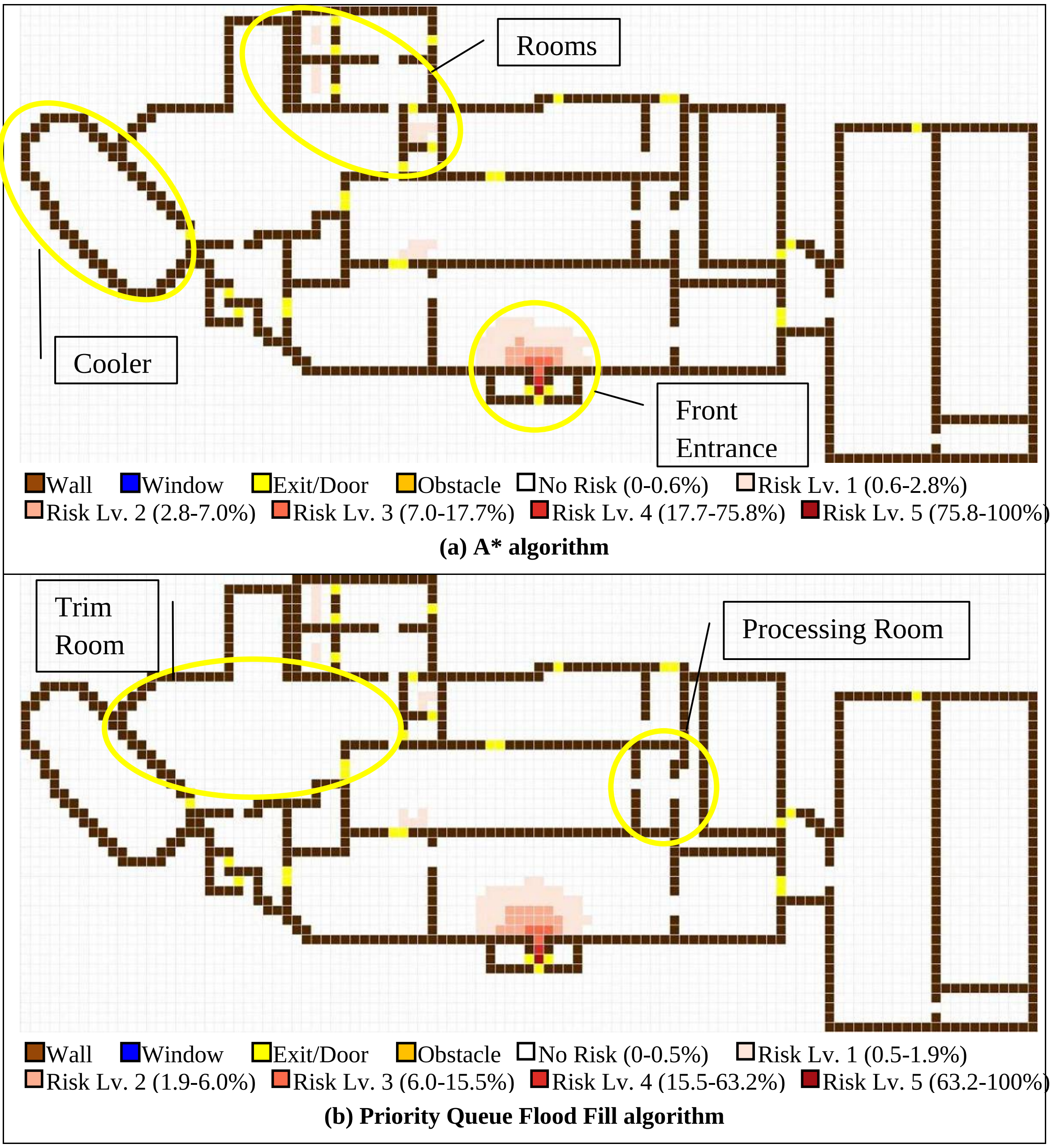


Figure 8-18 The potential death locations in the Hamlet chicken processing plant fire scenario

According to the distribution of deaths displayed above and in the fire report (Figure 6-22), five regions were appointed: front entrance (Region 1), cooler (Region 2), rooms (Region 3), space adjacent to processing room (Region 4), and trim room (Region 5). These regions are displayed on a grid-based map in Figure 8-19.

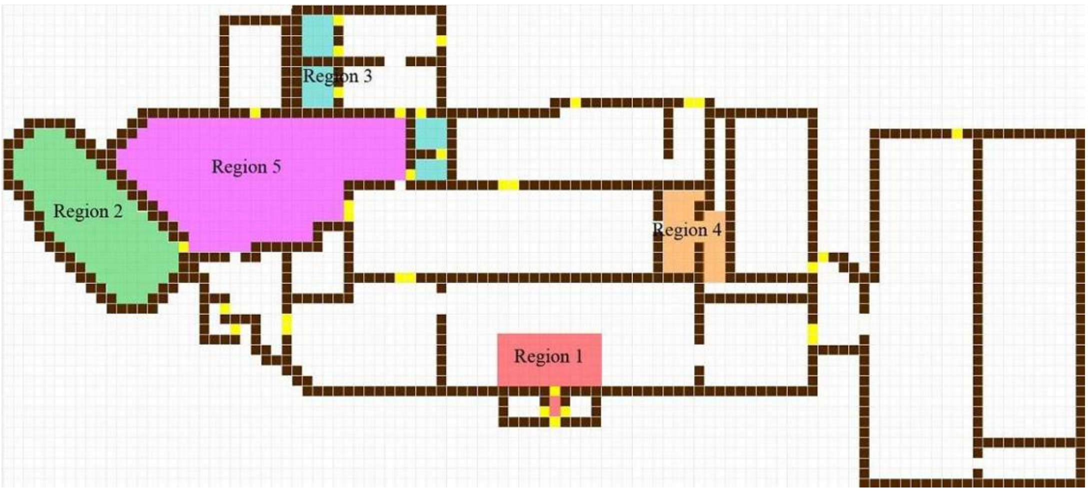


Figure 8-19 Region identification based on the distribution of deaths displayed on choropleth map and the information in the Hamlet chicken processing plant fire report

Figure 8-20 displays the number of deaths in each region of the Hamlet chicken processing plant scenario. Deaths in the simulations occurred in places where no occupants perished in the actual incident, and almost no pedestrian agents died in the places where many occupants expired in the cooler or processing room that were recorded in the fire report. In the model, a median value (0) that was calculated in region 3 leads to the only 100% of similarity when comparing to the fire report statistics (Table 8-10). Otherwise, the model simulated completely different results to the real incident.

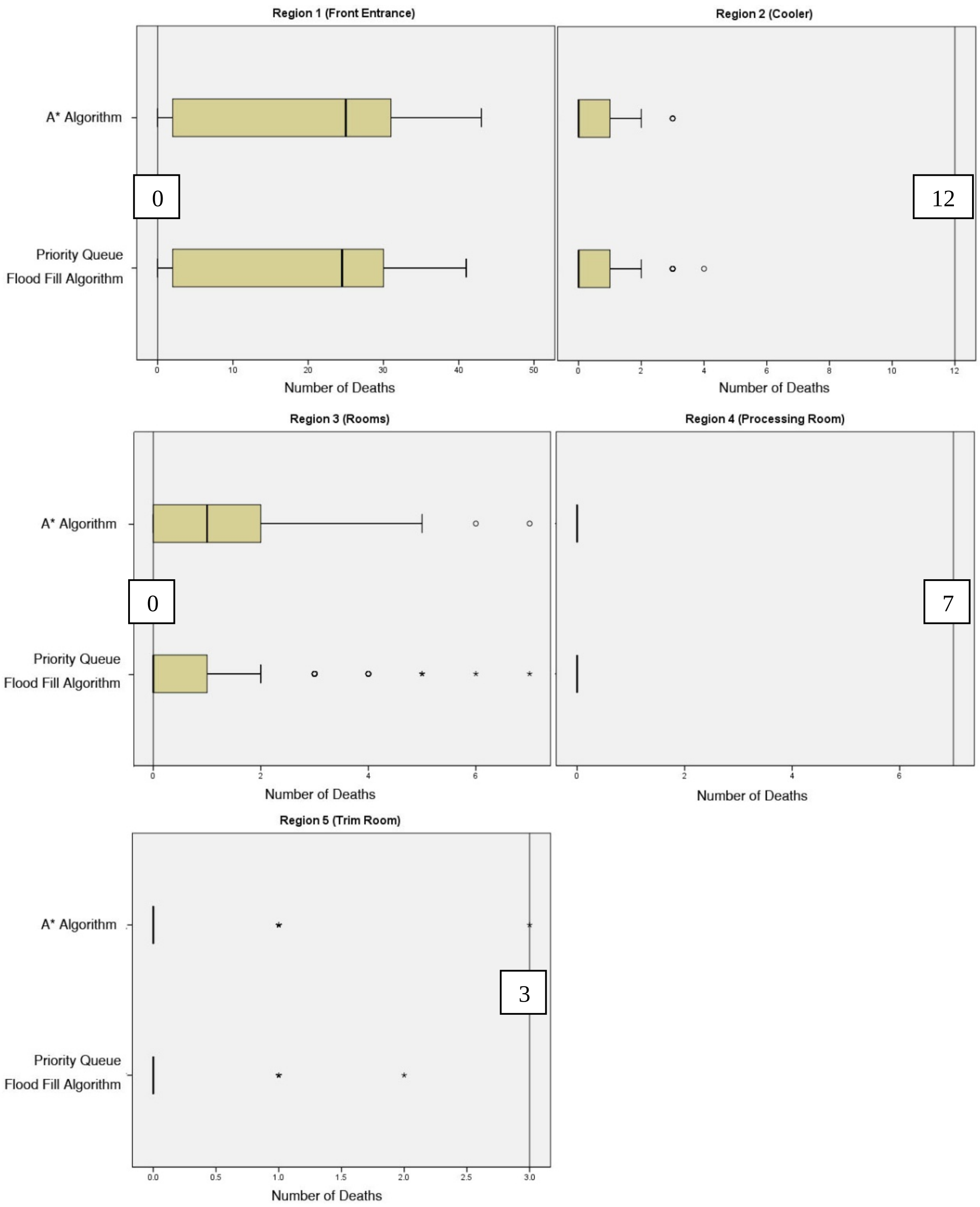


Figure 8-20 Number of deaths that occurred in region 1 to 5 (see Figure 8-19) using different navigation algorithms in the Hamlet chicken processing plant scenario (vertical lines: fire report statistics)

Table 8-10 Similarities of fire report statistics and the number of deaths by region (median value of 500 runs) in the Hamlet chicken processing plant scenario and statistical tests of the two navigation algorithms

Navigation Algorithms	**Region 1 (Front Entrance)**	**Region 2 (Cooler)**	**Region 3 (Rooms)**	**Region 4 (Processing Room)**	**Region 5 (Trim Room)**
A* Algorithm	0%	0%	0%	0%	0%
Priority Queue Flood Fill Algorithm	0%	0%	100%	0%	0%
Wilcoxon Signed Ranks Test on Algorithms	Accepted	Accepted	Rejected	Accepted	Accepted

Figure 8-21 and Table 8-11 show the big difference between the simulation results and the actual fire report statistics, which the percentages of similarities remain the same as the values in the previous table. Therefore, both navigation algorithms failed to reconstruct events at the Hamlet chicken processing plant fire. The behaviour of occupants stayed inside the cooler instead of evacuating through the nearest emergency exit, which was caused by no evacuation training provided to the employees (Section 6.4.3), is considered as a different behaviour than the behaviour designed in the model.

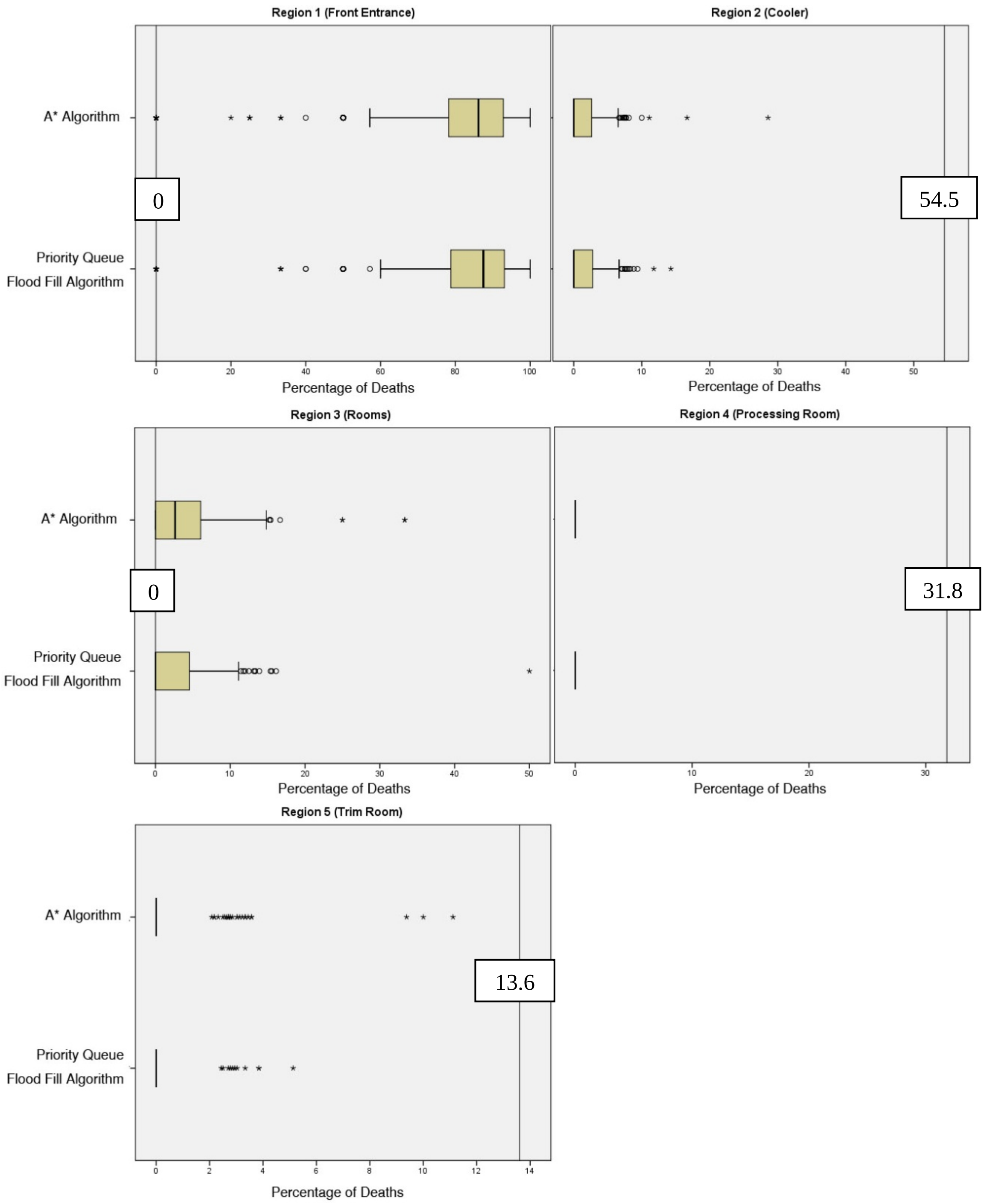


Figure 8-21 Percentage of deaths that occurred in region 1 to 5 using different navigation algorithms in the Hamlet chicken processing plant scenario (vertical lines: fire report statistics)

Table 8-11 Similarities of fire report statistics and the percentage of deaths by region (median value of 500 runs) in the Hamlet chicken processing plant scenario and statistical tests of the two navigation algorithms

Navigation Algorithms	**Region 1 (Front Entrance)**	**Region 2 (Cooler)**	**Region 3 (Rooms)**	**Region 4 (Processing Room)**	**Region 5 (Trim Room)**
A* Algorithm	0%	0%	0%	0%	0%
Priority Queue Flood Fill Algorithm	0%	0%	100%	0%	0%
Wilcoxon Signed Ranks Test on Algorithms	Accepted	Accepted	Rejected	Accepted	Accepted

8.2.5 Test 5: System Run Time

Processing time is one of the most important concerns when building an efficient evacuation model. The system run time was recorded from the moment a simulation started to the point at which it ended, and thus the time required for each run to finish the whole process of simulation was used to validate the processing speed for evacuation modelling. Before showing the results of system run time, Table 8-12 displays the parameters of each scenario, and the specification of the desktop computer is listed as follows:

- Manufacturer: Dell
- Model: Optiplex 980
- Processor: Intel® Core™ i5 CPU 650 @ 3.20GHz 3.19GHz
- Installed memory (RAM): 8.00 GB
- System type: 64-bit Operating System

Table 8-12 Parameters of the developed fire evacuation scenarios

Parameters	Gothenburg Dance Hall	Rhode Island Nightclub	Hamlet Chicken Processing Plant
Building Size (0.5m/grid)	71 × 21 = 1491 cells	67 × 43 = 2881 cells	105 × 47 = 4935 cells
Number of Pedestrian Agents	400	458	90
Number of Door Agents	12 (4 for exits)	36 (8 for exits)	32 (6 for exits)
Number of Windows	24	26	0

Table 8-13 shows the system run time that the computer spent on simulating the Gothenburg dance hall evacuation scenario (400 runs), the Rhode Island nightclub evacuation scenario (500 runs), and the Hamlet chicken processing plant evacuation scenario (500 runs). In general, the greater the number of grids and agents involved in a scenario, the longer the time required to finish the process of calculation. According to the results, the Rhode Island nightclub took the longest time of these three cases, taking about two minutes to finish a run; the other two cases took less than a minute. None of the results meets the requirement of fast processing speed (less than 15 seconds). However, this would not influence the identification of the model as this thesis aims to develop a model for realisation or prediction purposes, which consider high quality and accuracy of results rather than the speed of simulation. This section concludes that the Priority Queue Flood Fill algorithm calculation was faster than the A* algorithm.

Table 8-13 System run time (in seconds) that the computer spent on one simulation run using different navigation algorithms in three fire scenarios

Navigation Algorithms	Gothenburg Dance Hall	Rhode Island Nightclub	Hamlet Chicken Processing Plant
A* Algorithm	Median = 44 Q_1=41; Q_3=46	Median = 133 Q_1=114; Q_3=156	Median = 34 Q_1=16; Q_3=37
Priority Queue Flood Fill Algorithm	Median = 43 Q_1=41; Q_3=45	Median = 112 Q_1=107; Q_3=115	Median = 32 Q_1=7; Q_3=34
Wilcoxon Signed Ranks Test on Algorithms	Rejected	Rejected	Rejected

8.3 Chapter Summary

This chapter presented the main simulation outcomes using five different tests to validate the evacuation model. According to the definition (Section 3.5), the realism of the model is validated by egress selection, the accuracy is confirmed by evacuation time and risk area identification, and processing speed is established by system run time. However, the fire reports lacked some information, so some of the simulation results cannot be compared to fire statistics, which represent what happened in real life. The number of evacuees (test 1, Rhode Island nightclub model only) and the number and distribution of victims (tests 3 and 4) were compared to the fire statistics as an individual case study (Table 8-14).

Table 8-14 The percentages of similarities in terms of the comparisons between the simulation results and the fire report statistics

Validation	Test	Similarity	
		A*	PF
Gothenburg Dance Hall Scenario			
Accuracy	Number of Deaths	71.4	57.1
	Number of Injuries	85.0	84.4
	Number of Deaths in Region 1 (Corridor)	39.5	32.6
	Number of Deaths in Region 2 (Room)	20.0	25.0
	Number of Deaths in Region 3 (Corner)	0	0
	Number of Deaths in Region 4 (Bar Area)	0	0
	Percentage of Deaths in Region 1 (Corridor)	56.8	57.1
	Percentage of Deaths in Region 2 (Room)	28.4	40.4
	Percentage of Deaths in Region 3 (Corner)	0	0
	Percentage of Deaths in Region 4 (Bar Area)	0	0
Total Percentage of Similarities		301.0	296.6
Rhode Island Nightclub Scenario			
Realism	Number of Evacuees at Exit 1 (Front Entrance)	75.6	92.2
	Number of Evacuees at Exit 2 (Main Bar Side Exit)	17.4	6.5
	Number of Evacuees at Exit 3 (Platform Exit)	85.0	60.0
	Number of Evacuees at Windows	78.5	79.7
Accuracy	Number of Deaths	75.3	52.8
	Number of Injuries	90.4	98.7
	Number of Deaths in Region 1 (Entryway)	35.5	0
	Number of Deaths in Region 2 (Rooms)	57.1	71.4
	Number of Deaths in Region 3 (Storage Area)	70.0	60.0
	Number of Deaths in Region 4 (Dart room)	44.4	33.3
	Number of Deaths in Region 5 (Sunroom)	85.2	92.6
	Percentage of Deaths in Region 1 (Entryway)	67.0	56.3
	Percentage of Deaths in Region 2 (Rooms)	87.3	82.3
	Percentage of Deaths in Region 3 (Storage Area)	53.6	42.9
	Percentage of Deaths in Region 4 (Dart room)	31.7	22.8
	Percentage of Deaths in Region 5 (Sunroom)	65.3	64.0
Total Percentage of Similarities		989.3	915.5
Hamlet Chicken Processing Plant Scenario			
Accuracy	Number of Deaths	68.2	72.7
	Number of Injuries	53.7	53.7
	Number of Deaths in Region 1 (Front Entrance)	0	0
	Number of Deaths in Region 2 (Cooler)	0	0
	Number of Deaths in Region 3 (Rooms)	0	100
	Number of Deaths in Region 4 (Processing Room)	0	0
	Number of Deaths in Region 5 (Trim Room)	0	0
	Percentage of Deaths in Region 1 (Front Entrance)	0	0
	Percentage of Deaths in Region 2 (Cooler)	0	0
	Percentage of Deaths in Region 3 (Rooms)	0	100
	Percentage of Deaths in Region 4 (Processing Room)	0	0
	Percentage of Deaths in Region 5 (Trim Room)	0	0
Total Percentage of Similarities		121.9	326.4

In the Gothenburg dance hall simulation, the number of injuries was the result closest to the fire statistics. Following that, the next highest similarity occurred in the number of deaths. Of the 20 comparisons in both navigation algorithms, three percentages of similarity are higher than 70%, another three percentages are located between 50% and 70%, and the rest of percentages are less than 50%. In addition, the A* algorithm calculated slightly better results in terms of the total percentage of similarities.

More statistics were recorded in the Rhode Island nightclub fire report, so an additional test (egress selection) was compared to validate the realism of model. Of the 32 comparisons in both navigation algorithms, 14 percentages of similarity are higher than 70%, nine of them are 50-70%, and another nine percentages are below 50% of similarity. Overall, the similarities of egress selection show high realism of the model when comparing the results to the actual fire report statistics. Same as the Gothenburg dance hall simulation results, the number of injuries was identified as the highest percentage of similarity and the results that were calculated by the A* algorithm were better than the Priority Queue Flood Fill algorithm.

The results of the Hamlet chicken processing plant simulations are different to the previous two scenarios. For example, the highest percentage of similarity is the number of deaths rather than the number of injuries, and the Priority Queue Flood Fill algorithm calculated better results than the A* algorithm in terms of the total percentage of similarities. Of the 24 comparisons using both navigation algorithms, two 100 percents of similarities were identified in the number and percentage of deaths in region 3 by the Priority Queue Flood Fill algorithm. The percentages of similarity for the number of deaths and injuries are located between 50% and 75%. The rest of the results are completely different to the actual fire incident.

Further to the comparisons above, the evacuation time (test 1) was displayed to identify a potential safe evacuation time during which occupants could survive the fire. According to the simulation results, evacuees spent about 4.5 minutes to evacuate from the Gothenburg dance hall while another group of evacuees spent less than four minutes to escape safely from the Rhode Island nightclub, and the evacuation time of the Hamlet chicken processing plant scenario is about 2.5 minutes. Finally, system run time (test 5) was recorded to validate the processing speed of the model.

The above displayed the simulation results of the 0.5 m^2 grid-based model in three different scenarios. The 0.3 m^2 grid-based model was developed to identify the influence of the smaller grid size (Section 9.2). In addition, the Rhode Island nightclub scenario, which contains more fire statistics in the fire report and high percentages of similarity over the tests, was modified to simulate different situations that might occur in the building (Section 9.3).

9. Simulation Outcomes of Different Grid Sizes and Scenarios

Introduction and Background	Contents of Evacuation Modelling	Developing Research Questions	Developing an Evacuation Model	Simulation Outcomes	Discussion	Conclusion and Further Work
Ch. 1	Ch. 2	Ch. 3	Ch. 4, 5 and 6	Ch. 7, 8 and 9	Ch. 10	Ch. 11

9.1 Introduction

The previous chapter presented the main results from the evacuation model using five tests in three different evacuation scenarios. This chapter presents the results from a model with a different grid size and five proposed scenarios of the Rhode Island nightclub are established by modifying parameters in the model.

A smaller grid size (0.3 m^2) is proposed to accommodate a smaller human body size to simulate situations where people are squeezed together in a high-density space (Section 9.2). The results from the 0.3 m^2 grid-based scenario are compared with the results from the 0.5 m^2 grid-based scenario displayed in the previous chapter. In addition, a number of model parameters such as the number of pedestrian agents, exit accessibility, the origin of the fire and building configuration are modified in order to understand safety under different conditions in the Rhode Island nightclub. The results from the five scenarios are compared with each other, as well as with the fire statistics (Section 9.3).

9.2 Tests using Different Grid Sizes

Section 8.2 displayed the results of the 0.5 m^2 grid-based scenario using three fire evacuation scenarios: the Gothenburg dance hall, the Rhode Island nightclub and the Hamlet chicken processing plant fires. In the 0.3 m^2 grid-based scenario, the building configuration of each fire case is designed with 0.3 m^2 cells; the parameters other than grid size remain the same as the 0.5 m^2 grid-based scenario. This section compares the results from calculations using two different grid sizes. The results of statistical tests are displayed in Table 10-1.

9.2.1 Test 1: Egress Selection

Case 1: Gothenburg Dance Hall

Figure 9-1 displays the number of pedestrian agents who evacuated through each external route in the Gothenburg dance hall scenario. According to the results, over half of the total pedestrian agents (400) evacuated through the main exit in the 0.3 m^2 grid-based scenario. The total number of evacuees in the 0.5 m^2 grid-based scenario was 310 (A* algorithm) and 327 (Priority Queue Flood Fill algorithm), whereas the number of escapees in the 0.3 m^2 grid-based scenario increased by about 40 in both navigation algorithms.

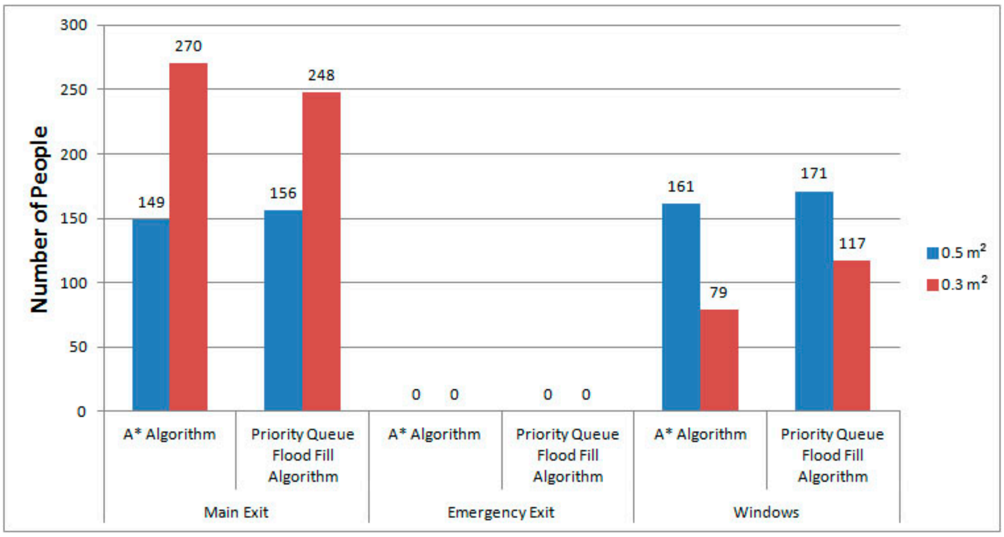


Figure 9-1 Number of evacuees (median value of 400 runs) at different egress routes using different navigation algorithms in the 0.3 m^2 and 0.5 m^2 grid-based Gothenburg dance hall scenarios

Case 2: Rhode Island Nightclub

Figure 9-2a displays the number of pedestrian agents who evacuated through each exit or window in the Rhode Island nightclub evacuation scenario. In the 0.3 m^2 grid-based scenario, more than 39% (A* algorithm) and 62% (Priority Queue Flood Fill algorithm) of the total pedestrian agents (458) evacuated through the front entrance, between 13% and 19% used windows to escape, and a few number of pedestrian agents used other exits. The number of pedestrian agents who escaped through the front entrance increased from 112 to 181 (A* algorithm) and from 83 to 287 (Priority Queue Flood Fill algorithm) in the 0.3 m^2 grid-based scenario, meaning that the results were 1.5 to 3.5 times greater than simulated in the 0.5 m^2 grid-based scenario. In addition, the similarities between the simulation results and the fire statistics were calculated as displayed in Figure 9-2b. In the 0.3 m^2 grid-based Rhode Island nightclub model, the similarities of the number of evacuees at three exits were completely different to fire statistics.

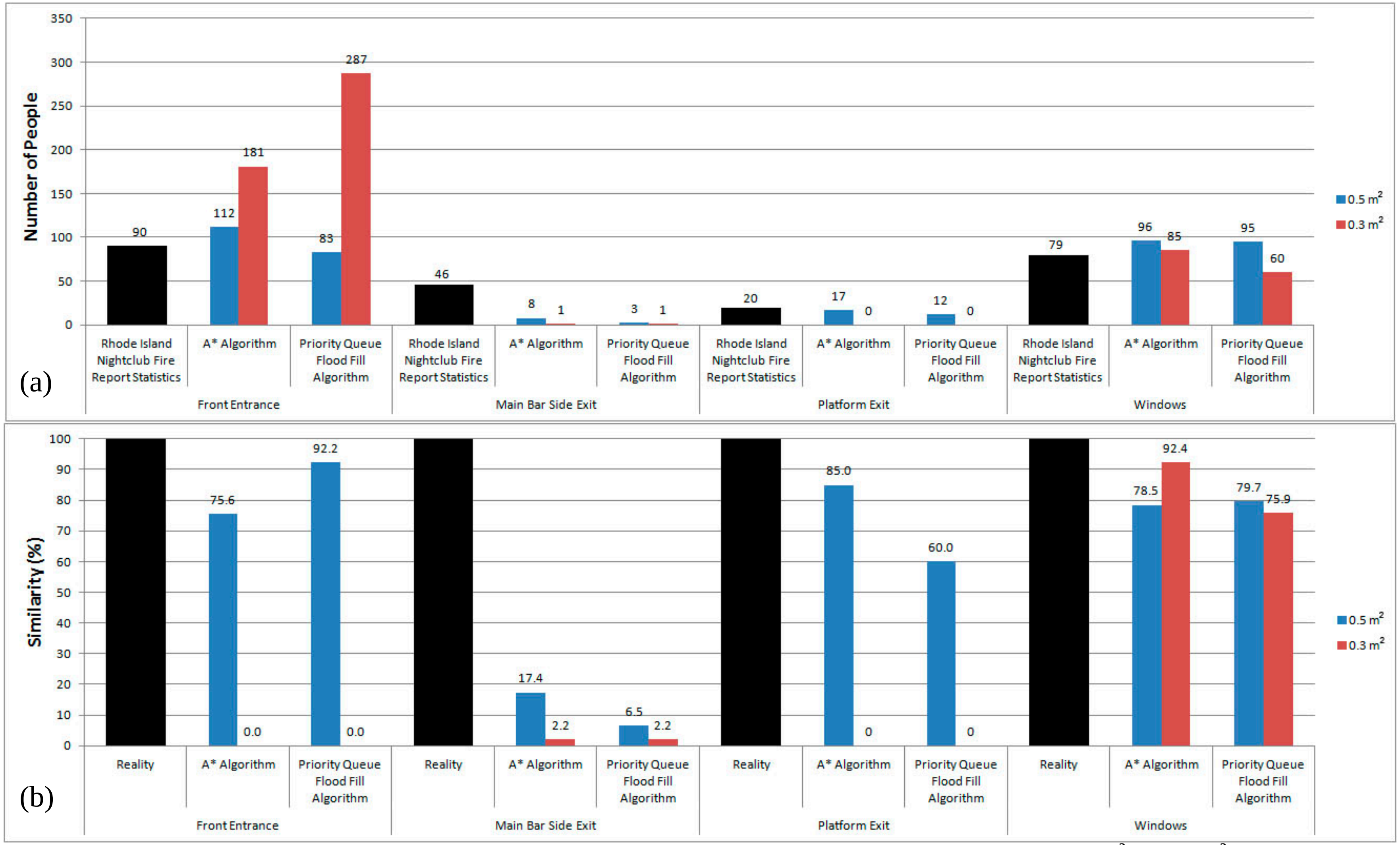


Figure 9-2 Number of evacuees (median value of 500 runs) at different egress routes using different navigation algorithms in 0.3 m^2 and 0.5 m^2 grid-based Rhode Island nightclub scenarios, displaying (a) the actual numbers of evacuees and (b) the similarities between simulation results and fire statistics

Case 3: Hamlet Chicken Processing Plant

In both grid-based Hamlet chicken processing plant scenarios, all the evacuees evacuated through the main entrance (Figure 9-3). The number of pedestrian agents who evacuated safely in the 0.5 m^2 grid-based scenario was about 1/3 of the number in the 0.3 m^2 grid-based scenario. In addition, 56.4% (A* algorithm) and 64.2% (Priority Queue Flood Fill algorithm) of the total simulation runs (500) using the 0.3 m^2 grid-based scenario simulated all pedestrian agents surviving without being injured. This shows that the pedestrian agents have a higher opportunity to evacuate safely when simulating evacuation movement in a smaller grid size model.

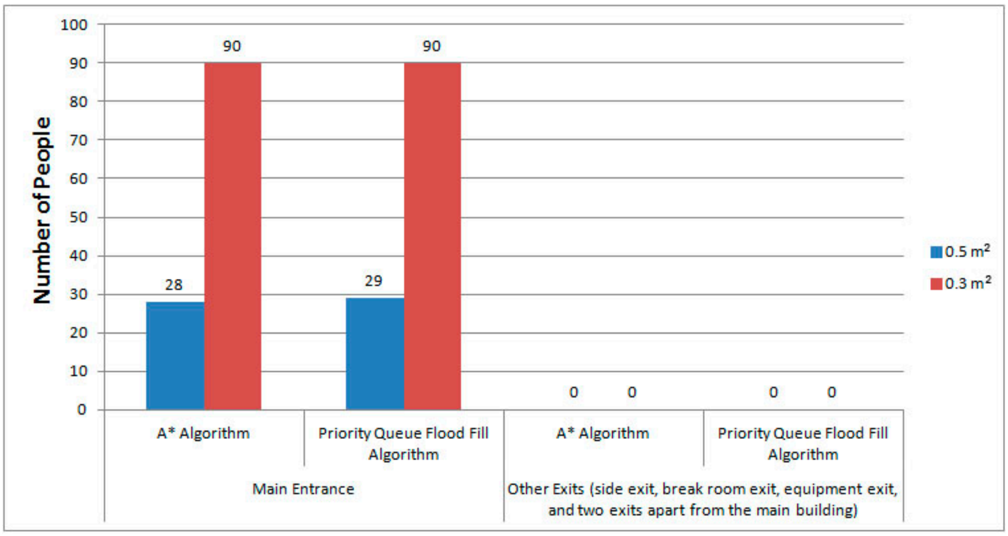


Figure 9-3 Number of evacuees (median value of 500 runs) at different egress routes using different navigation algorithms in the 0.3 m^2 and 0.5 m^2 Hamlet chicken processing plant scenarios

9.2.2 Test 2: Evacuation Time

Case 1: Gothenburg Dance Hall

Figure 9-4 shows the average evacuation time that total pedestrian agents spent exiting from each exit or windows. Although more pedestrian agents evacuated through the main exit in the 0.3 m^2 grid-based scenario, the decrease in the evacuation time represents a faster evacuation flow than in the 0.5 m^2 grid-based scenario. No pedestrian agents used emergency exit during the simulation, because this exit was not available for evacuation after the fire spread through the space. Instead, pedestrian agents used windows to escape from fire, which the evacuation time at windows represents the time that pedestrian agents could be rescued from windows or decided to jump before they perishing in the scene.

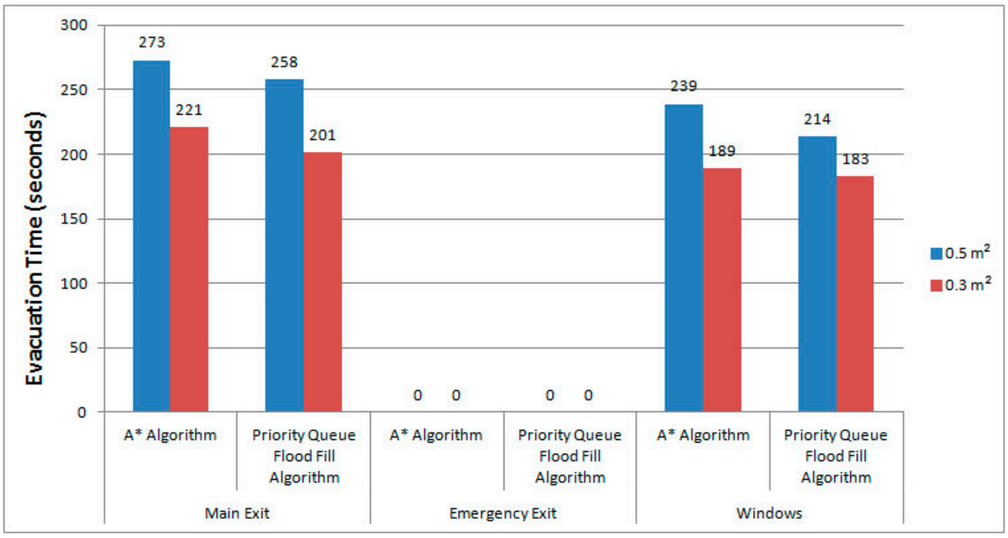


Figure 9-4 Evacuation time (median value of 400 runs) at exit or windows using different navigation algorithms in the 0.3 m^2 and 0.5 m^2 grid-based Gothenburg dance hall scenarios

Case 2: Rhode Island Nightclub

According to the spread of fire in the Rhode Island nightclub scenario, the platform exit, which was the nearest exit to the fire, was the first to be covered by the fire/smoke agents. Figure 9-5 shows the time that the last evacuee passed through the platform exit, at which point the door is blocked, forcing pedestrian agents to find an alternative route through the building after 42-44 seconds (0.5 m^2 grid-based scenario). According to the results of both the grid-based scenarios, the last evacuees usually passed through the front entrance, which recorded the longest evacuation time compared to other exits. Although the number of pedestrian agents at the front entrance in the 0.3 m^2 grid-based scenario was about three times the number in the 0.5 m^2 grid-based scenario (see Figure 9-2a, Priority Queue Flood Fill algorithm), the evacuation flow was faster and evacuation time was reduced by about 50 seconds.

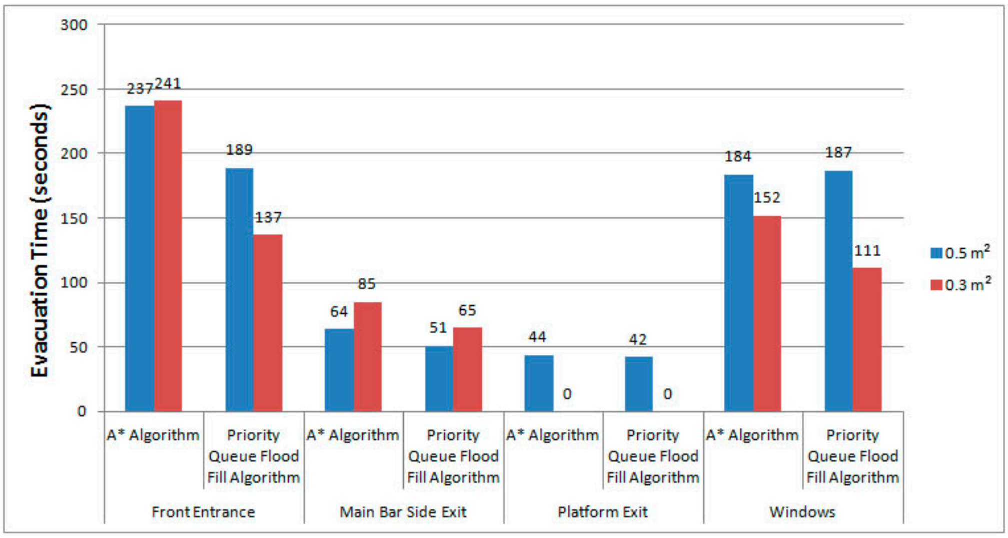


Figure 9-5 Evacuation time (median value of 500 runs) at exit or windows using different navigation algorithms in the 0.3 m^2 and 0.5 m^2 grid-based Rhode Island nightclub scenarios

Case 3: Hamlet Chicken Processing Plant

In the 0.3 m^2 grid-based Hamlet chicken processing plant scenario, the greater exit capacity of the front door led to more people evacuating safely from the building (see Figure 9-3), as well as a decrease in their evacuation time (Figure 9-6). None of the pedestrian agents used other exits during evacuation, so the evacuation time at the main entrance represents the overall evacuation time determined to escape safely from the building. In the 0.5 m^2 grid-based scenario, 28 out of 90 pedestrian agents spent about 2.5 minutes to evacuate safely from the building and the rest of the agents died or injured. In the 0.3 m^2 grid-based scenario, all pedestrian agents spent less than a minute to evacuate from the building.

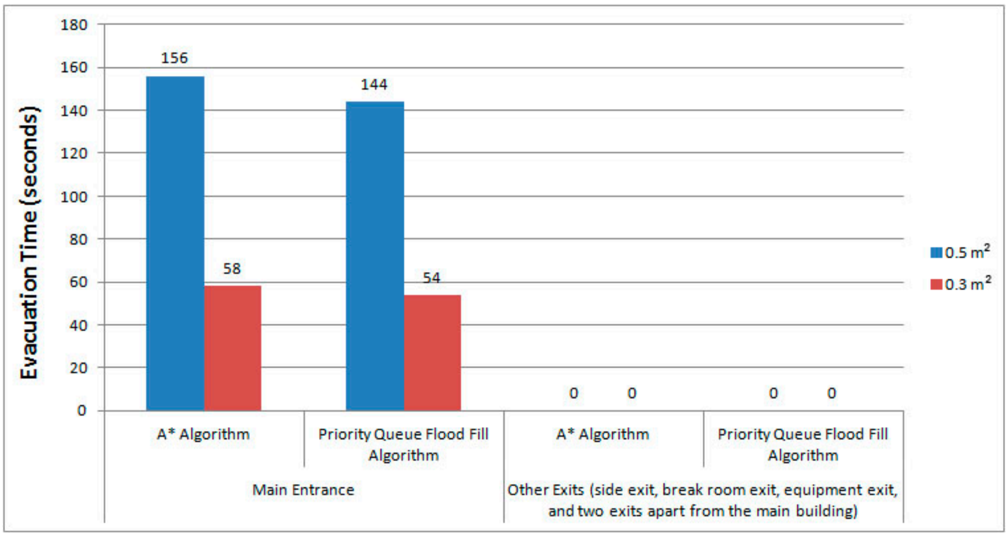


Figure 9-6 Evacuation time (median value of 500 runs) at exit or windows using different navigation algorithms in the 0.3 m^2 and 0.5 m^2 grid-based Hamlet chicken processing plant scenarios

9.2.3 Test 3: Numbers of Deaths and Injuries

Case 1: Gothenburg Dance Hall

The numbers of deaths and injuries that were simulated in the 0.5 m^2 and 0.3 m^2 grid-based Gothenburg dance hall scenarios are presented in Figure 9-7. Numbers of both deaths and injuries decreased significantly in the 0.3 m^2 grid-based scenario. For example, less than half of the deaths occurred in the 0.3 m^2 grid-based building, causing the similarities with the fire statistics to decrease to less than 30% (Figure 9-7b). In addition to the number of deaths, the number of injuries in the 0.3 m^2 grid-based scenario dropped to 55% (A* algorithm) and 66% (Priority Queue Flood Fill algorithm) of the numbers in the 0.5 m^2 grid-based scenario.

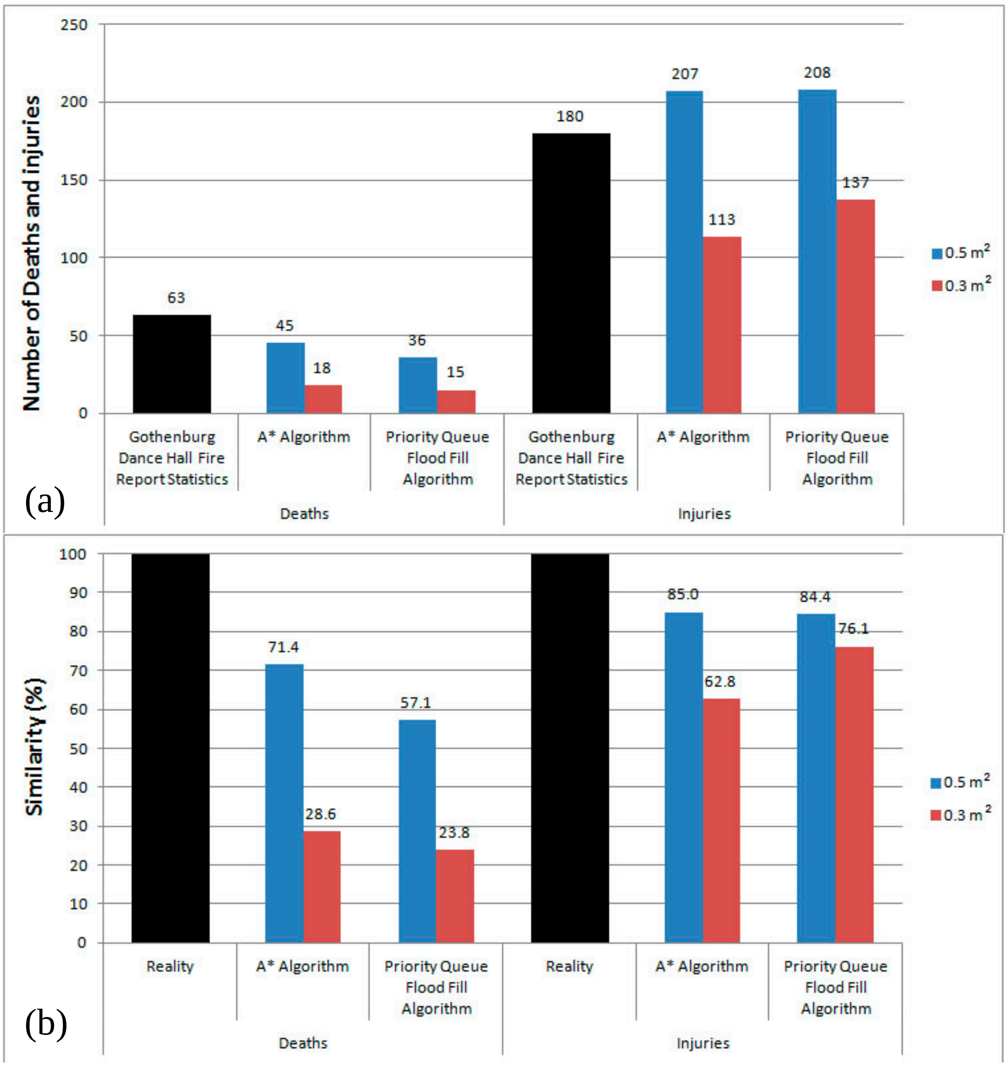


Figure 9-7 Number of deaths and injuries (median value of 400 runs) using different navigation algorithms in the 0.3 m^2 and 0.5 m^2 grid-based Gothenburg dance hall scenarios, displaying (a) the actual numbers of deaths and injuries and (b) the similarities between simulation results and fire statistics

Case 2: Rhode Island Nightclub

The number of deaths and injuries simulated in the 0.5 m^2 and 0.3 m^2 grid-based Rhode Island nightclub model are displayed in Figure 9-8. Same as the case of the Gothenburg dance hall model, both numbers of deaths and injuries decreased in the 0.3 m^2 grid-based model. The number of deaths and injuries that were calculated by the Priority Queue Flood Fill algorithm decreased by more than 60% of people in the 0.3 m^2 grid-based model, representing a low similarity to the actual number of victims in the real fire event.

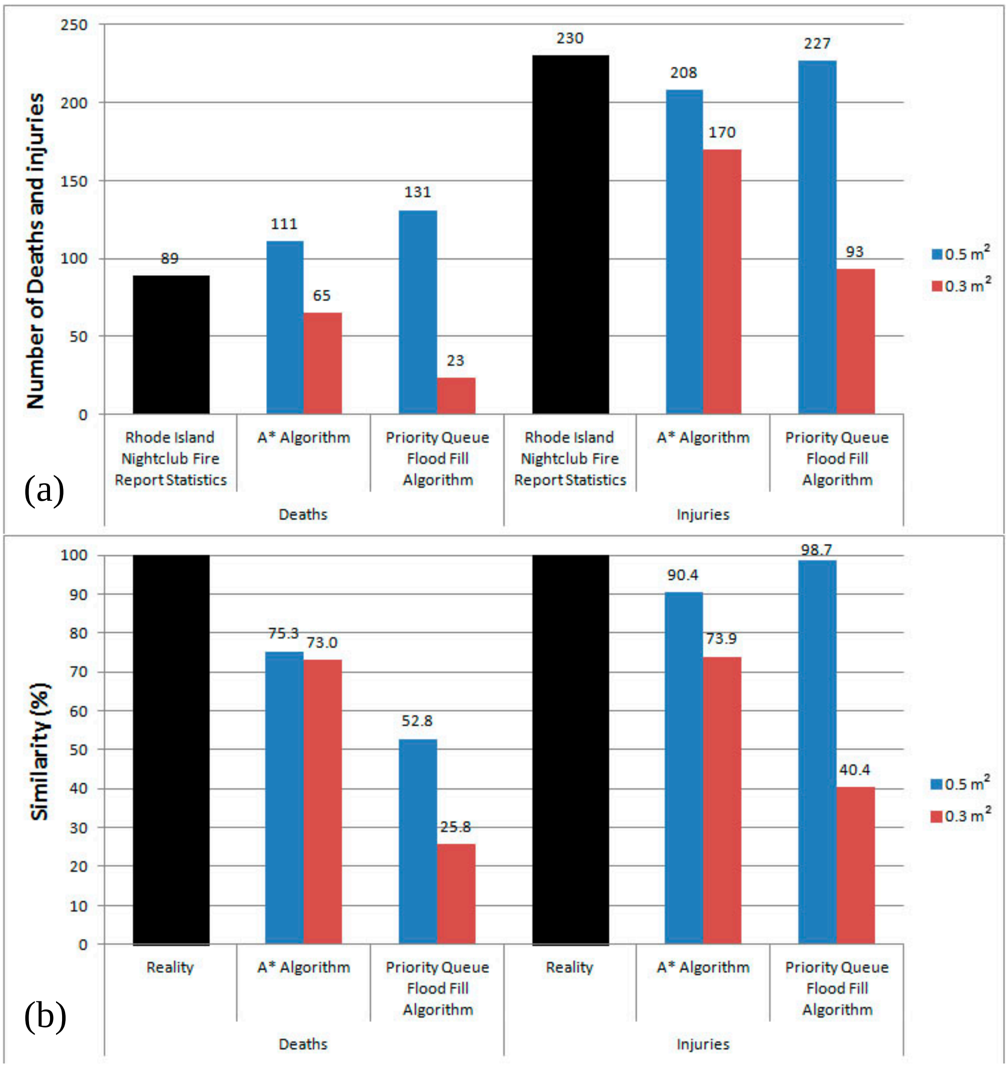


Figure 9-8 Number of deaths and injuries (median value of 500 runs) using different navigation algorithms in the 0.3 m^2 and 0.5 m^2 grid-based Rhode Island nightclub scenarios, displaying (a) the actual numbers of deaths and injuries and (b) the similarities between simulation results and fire statistics

Case 3: Hamlet Chicken Processing Plant

The number of deaths and injuries calculated in the 0.5 m^2 and 0.3 m^2 grid-based Hamlet chicken processing plant scenarios are displayed in Figure 9-9. As noted in Figure 9-3, all pedestrian agents successfully evacuated from the building before anyone died or injured in the 0.3 m^2 grid-based scenario. Therefore, similarities with the fire statistics in the 0.3 m^2 grid-based scenario show rapid decreases to zero.

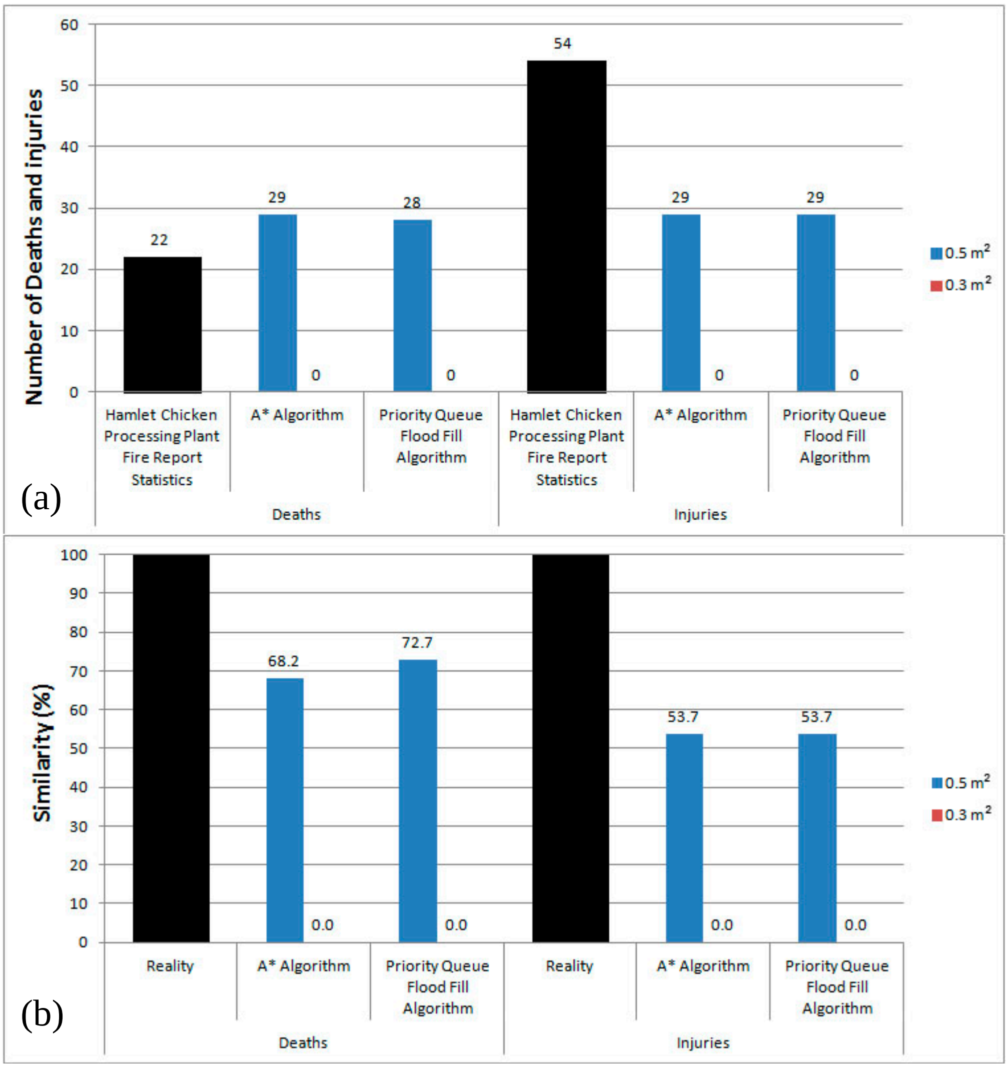


Figure 9-9 Number of deaths and injuries (median value of 500 runs) using different navigation algorithms in the 0.3 m^2 and 0.5 m^2 grid-based Hamlet chicken processing plant scenarios, displaying (a) the actual numbers of deaths and injuries and (b) the similarities between simulation results and fire statistics

9.2.4 Test 4: Distribution of Deaths

Case 1: Gothenburg Dance Hall

A smaller size of cells in the 0.3 m^2 grid-based Gothenburg dance hall scenario admitted a higher density of pedestrians, from four people per m^2 to nine people per m^2, so more pedestrian agents could enter the corridor. In addition, since the size of the exit increased from two cells to three cells, this enabled more pedestrian agents to evacuate the building (see Figure 9-1). The choropleth maps that show the distribution of deaths in the 0.3 m^2 grid-based Gothenburg dance hall scenario are displayed in Appendix D. According to Figure 9-10a, the number of deaths in regions 1, 3 and 4 calculated in the 0.3 m^2 grid-based scenario decreased by more than half from the numbers that were calculated in the 0.5 m^2 grid-based scenario. Figure 9-10b shows similarities to the fire statistics increased in regions 2, 3 and 4 of the 0.3 m^2 grid-based scenarios, especially in the areas of the corner (Region 3) and bar (Region 4) where no pedestrian agents died, meaning an increase in similarities to 100%.

Figure 9-11a shows the death occurrence rate for each region in the 0.5 m^2 and 0.3 m^2 grid-based Gothenburg dance hall scenarios. The percentage of deaths in Region 2 calculated by both algorithms in the 0.3 m^2 grid-based scenario were almost five times those calculated in the 0.5 m^2 grid-based scenario. The similarity of the percentage of deaths to the statistics in Region 2 increased to 68.5% when calculated by the A* algorithm, but dropped to 2.8% when using the Priority Queue Flood Fill algorithm (Figure 9-11b).

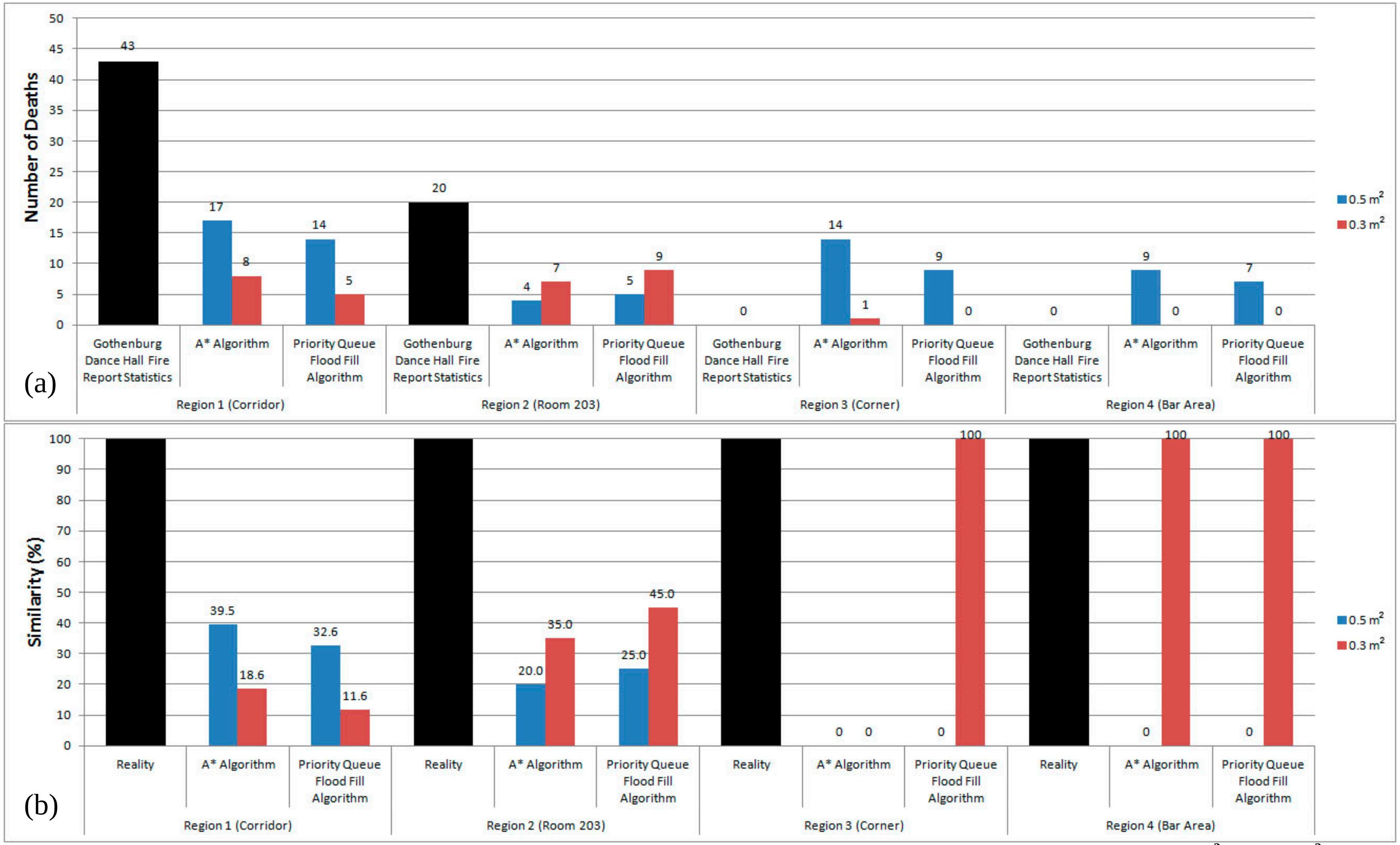


Figure 9-10 Numbers of deaths (median value of 400 runs) that occurred in each region using different navigation algorithms in the 0.3 m^2 and 0.5 m^2 grid-based Gothenburg dance hall scenario, displaying (a) the actual numbers of deaths and (b) similarities between the simulation results and fire statistics

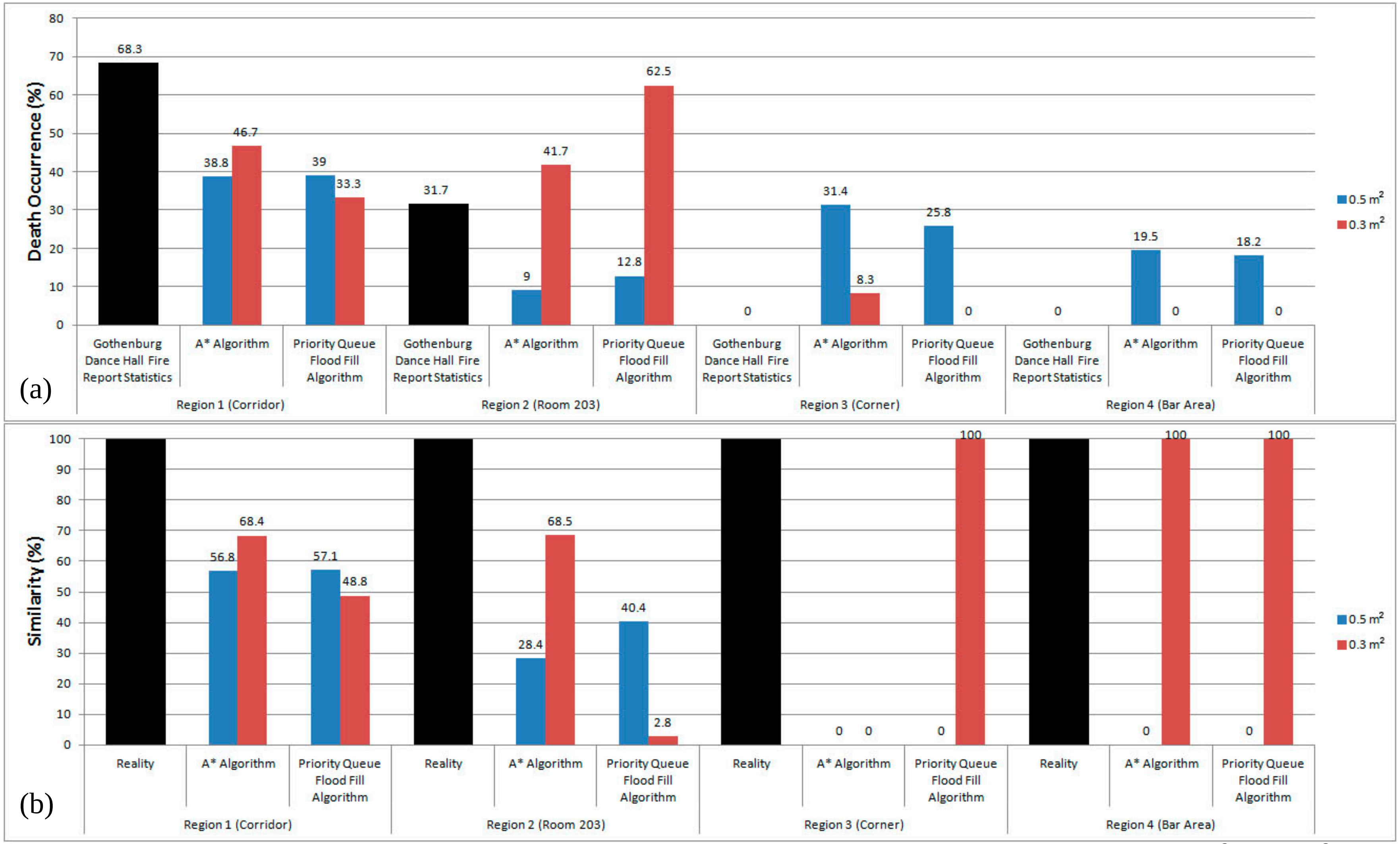


Figure 9-11 Percentage of deaths (median value of 400 runs) that occurred in each region using different navigation algorithms in the 0.3 m^2 and 0.5 m^2 grid-based Gothenburg dance hall scenario, displaying (a) the actual numbers of deaths and (b) similarities between the simulation results and fire statistics

Case 2: Rhode Island Nightclub

The choropleth maps that show the distribution of deaths in the 0.3 m^2 grid-based Rhode Island nightclub scenario are displayed in Appendix D. According to Figure 9-12a, two significant decreases occurred in the case of the 0.3 m^2 grid-based scenario, namely the number of deaths at the front entrance (Region 1) and in the Sunroom (Region 5). In the smaller grid-based scenario, exits with a greater capacity enabled more pedestrian agents to evacuate through the main entrance before they perished (see Figure 9-2). Therefore, fewer pedestrian agents died around the exit in the 0.3 m^2 grid-based scenario (Figure 9-12a). Although both the number of deaths in the entryway (Region 1) and the Sunroom (Region 5) dropped to less than half the numbers that occurred in the 0.5 m^2 grid-based scenario, the similarities with fire statistics in the entryway increased (both algorithms) and another decreased (Figure 9-12b).

Figure 9-13a shows the percentage of deaths at each region in the 0.5 m^2 and 0.3 m^2 grid-based Rhode Island nightclub scenarios. The highest risk areas in the 0.5 m^2 grid-based scenario were similar to the actual fire disaster, in which deaths mainly occurred near the front entrance and the sunroom. On the other hand, the distribution of pedestrian agents who died in places such as the rooms and storage area in the 0.3 m^2 grid-based scenario was relatively greater, which was caused by more pedestrian agents evacuated successfully through the main exit. In Figure 9-13b, the similarities in deaths between the model and the statistics in the 0.3 m^2 grid-based scenario were generally lower than in the 0.5 m^2 grid-based scenario.

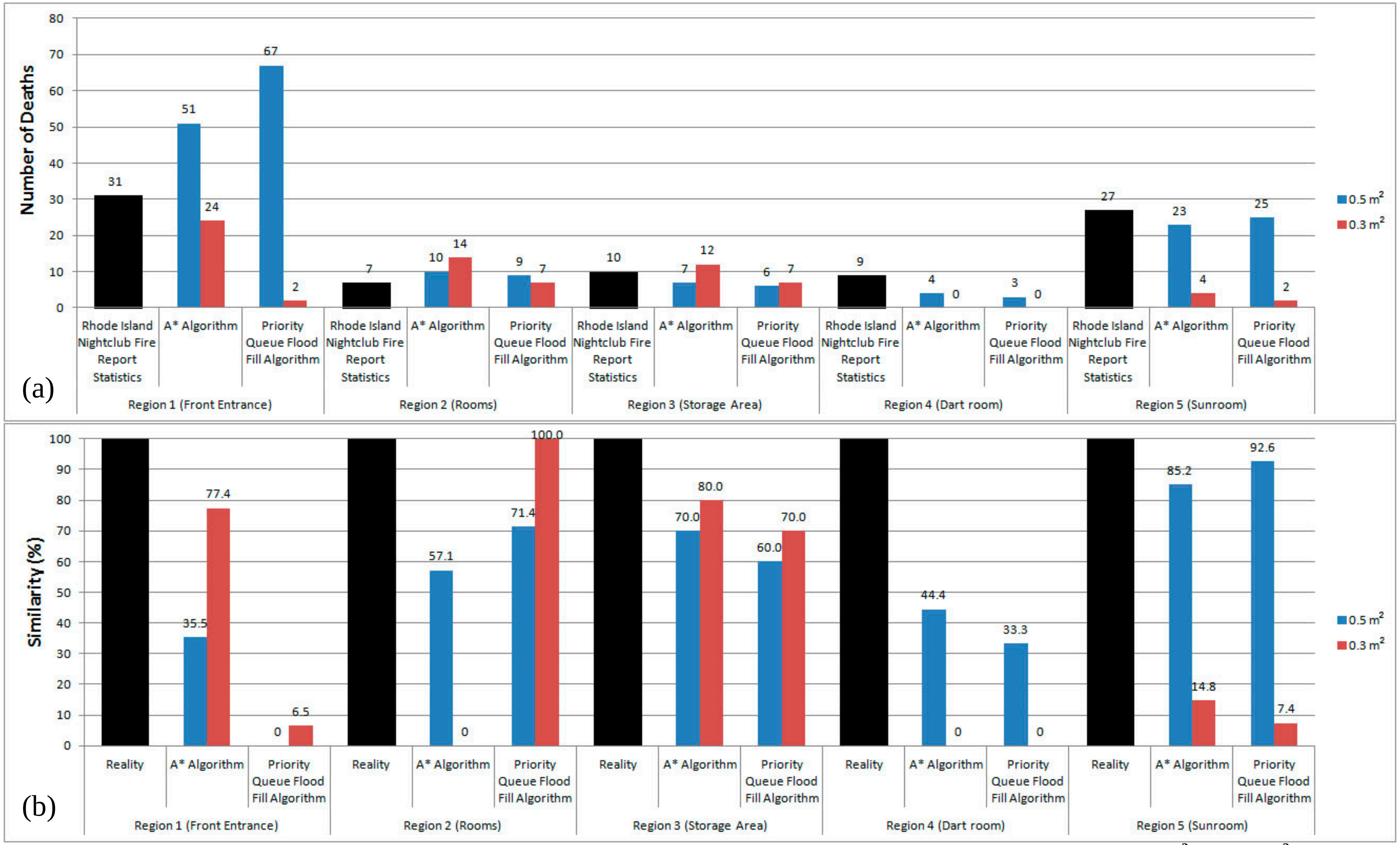


Figure 9-12 Numbers of deaths (median value of 500 runs) that occurred in each region using different navigation algorithms in the 0.3 m^2 and 0.5 m^2 grid-based Rhode Island nightclub scenario, displaying (a) the actual numbers of deaths and (b) similarities between the simulation results and fire statistics

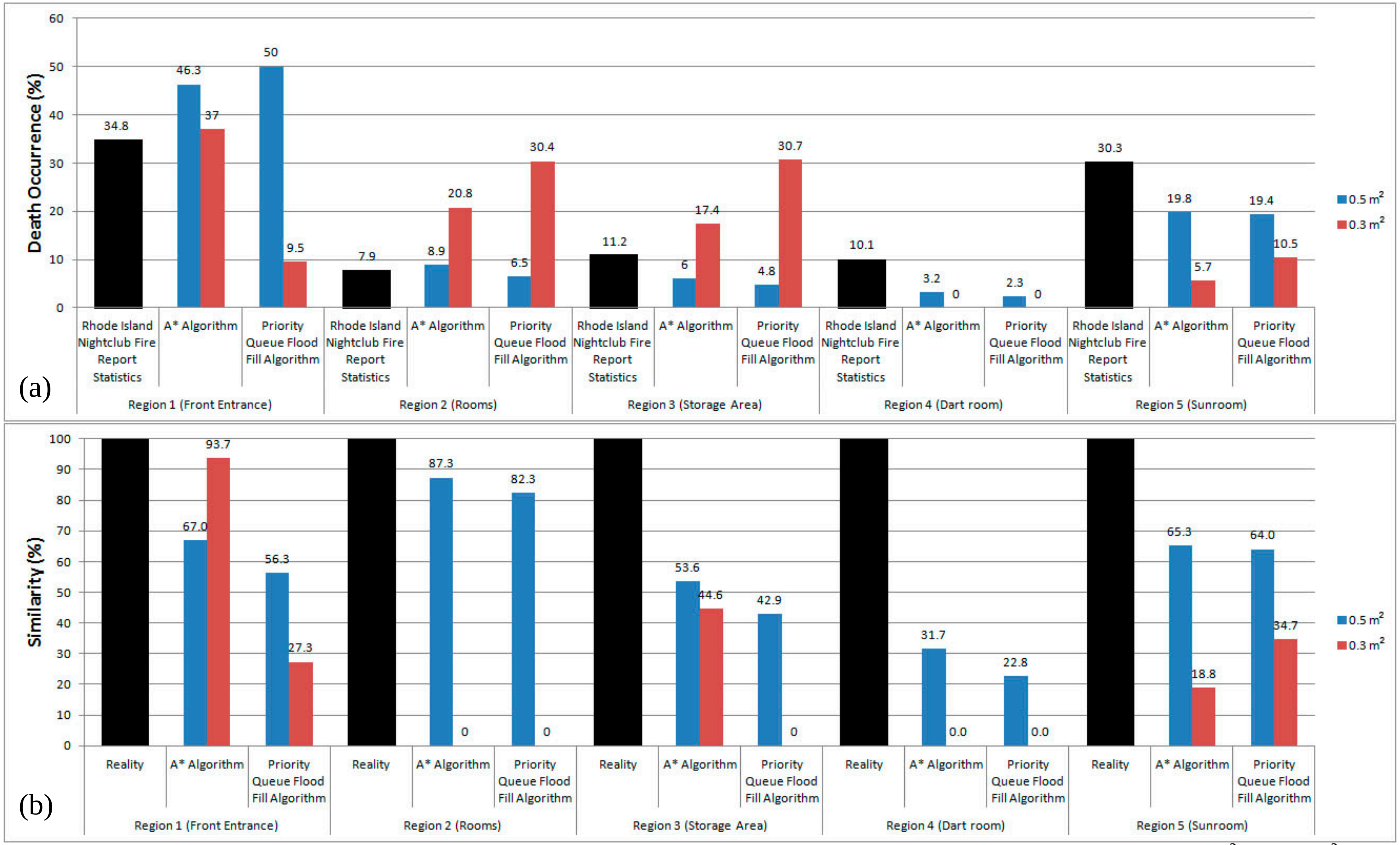


Figure 9-13 Percentage of deaths (median value of 500 runs) that occurred in each region using different navigation algorithms in the 0.3 m^2 and 0.5 m^2 grid-based Rhode Island nightclub scenario, displaying (a) the actual numbers of deaths and (b) similarities between the simulation results and fire statistics

Case 3: Hamlet Chicken Processing Plant

In the 0.5 m^2 grid-based scenario, pedestrian agents who died mainly occurred at the front entrance (Region 1), whereas none occurred in the 0.3 m^2 grid-based scenario. According to Figure 9-9, none of the pedestrian agents died in the 0.3 m^2 grid-based scenario, resulting no deaths showed in every region (Figure 9-14a). Figure 9-14b displays the similarities when the simulation results are compared to the fire statistics. As the model simulated all pedestrian agents survived from the fire, the front entrance and rooms where no deaths occurred in real fire incident were identified as 100% of similarity. The choropleth maps that show the potential death locations in the 0.3 m^2 grid-based Hamlet chicken processing plant scenario are displayed in Appendix D.

Figure 9-15a shows the percentage of deaths occurred in the 0.5 m^2 and 0.3 m^2 grid-based Hamlet chicken processing plant scenarios. In the 0.5 m^2 grid-based scenario, more than 85% of deaths occurred at the front entrance and few occurred in other defined regions. Therefore, the results show significant differences between the simulation results and the fire statistics (Figure 9-15b), since most pedestrian agents died around the main entrance rather than inside the cooler or in the rooms where the deaths occurred in the actual disaster. As mentioned above, no deaths occurred in the 0.3 m^2 grid-based scenario led to either 0% or 100% similarity. Overall, the model was considered to be a poor representation of the Hamlet chicken processing plant fire in terms of the extreme outcomes.

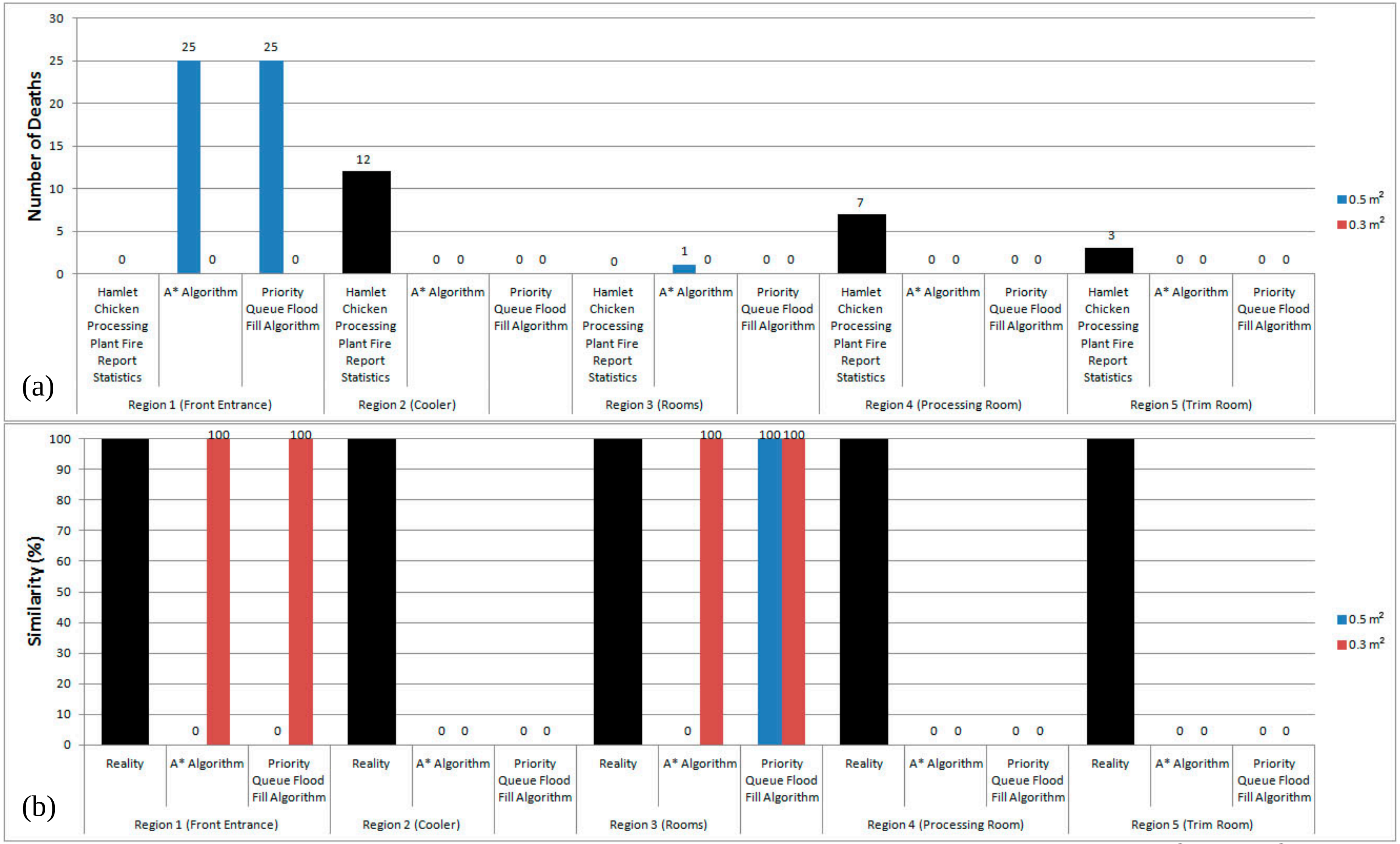


Figure 9-14 Numbers of deaths (median value of 500 runs) that occurred in each region using different navigation algorithms in the 0.3 m^2 and 0.5 m^2 grid-based Hamlet chicken processing plant scenario, displaying (a) the actual numbers of deaths and (b) similarities between the simulation results and fire statistics

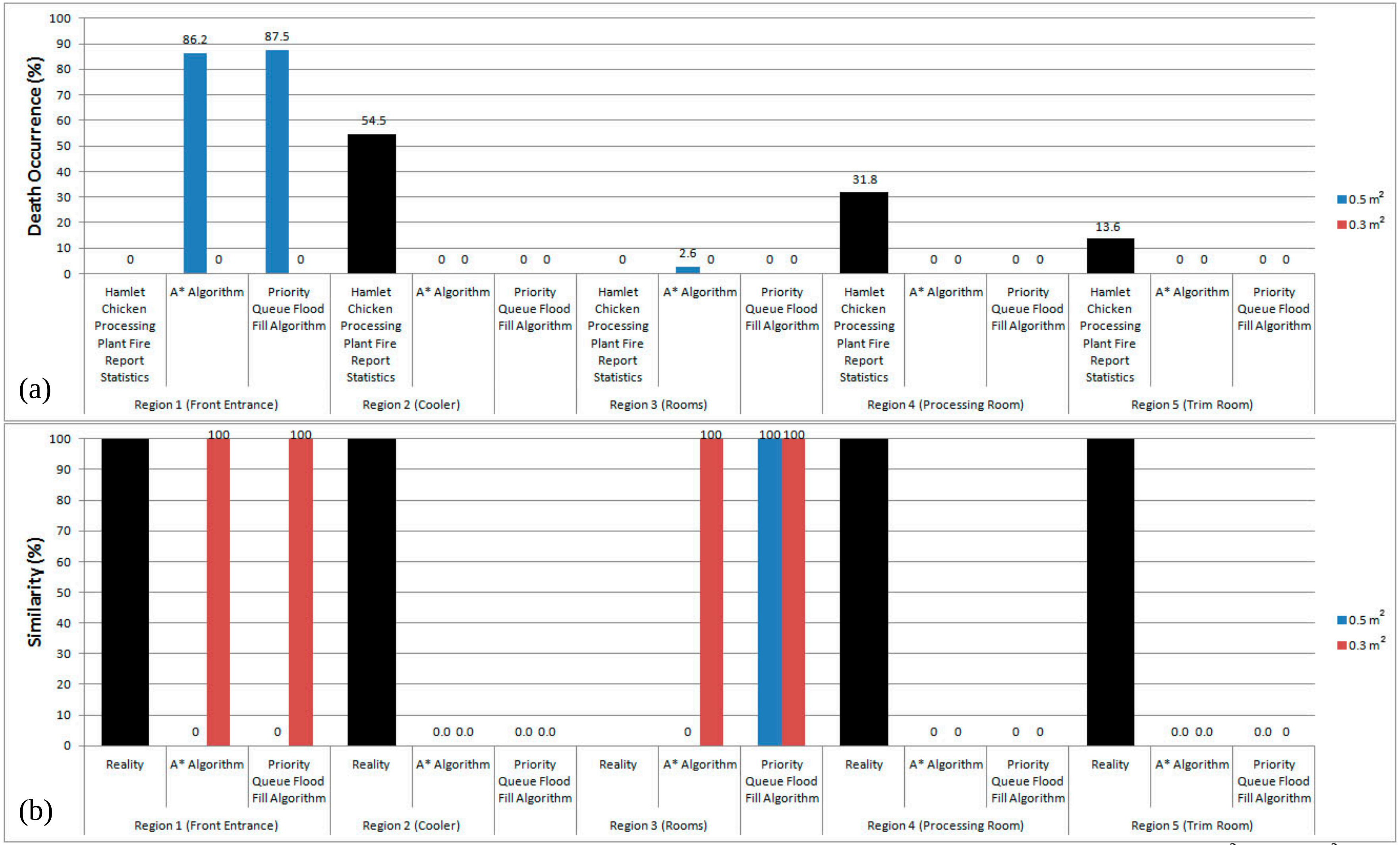


Figure 9-15 Percentage of deaths (median value of 500 runs) that occurred in each region using different navigation algorithms in the 0.3 m^2 and 0.5 m^2 grid-based Hamlet chicken processing plant scenario, displaying (a) the actual numbers of deaths and (b) similarities between the simulation results and fire statistics

9.2.5 Test 5: System Run Time

The model used the same desktop environment (see Section 8.2.5) for simulating evacuation movement in the 0.3 m^2 grid-based scenarios. Table 9-1 displays the number of grids and the number of different agents in the Gothenburg dance hall, the Rhode Island nightclub and the Hamlet chicken processing plant scenarios.

Table 9-1 Parameters of the 0.3 m^2 grid-based fire evacuation scenarios

Parameters	Gothenburg Dance Hall	Rhode Island Nightclub	Hamlet Chicken Processing Plant
Building Size (0.3m/grid)	120 × 33 = 3960 cells	112 × 68 = 7616 cells	148 × 64 = 9472 cells
Number of Pedestrian Agents	400	458	90
Number of Door Agents	18 (6 for exits)	58 (13 for exits)	55 (12 for exits)
Number of Windows	54	45	0

Figure 9-16 shows the median value of system run time the computer spent simulating both the 0.3 m^2 and 0.5 m^2 grid-based Gothenburg dance hall evacuation scenarios (400 runs), Rhode Island nightclub evacuation scenarios (500 runs) and Hamlet chicken processing plant evacuation scenarios (500 runs). Based on the number of building cells and the number of agents, the Rhode Island nightclub scenario required the most complex calculations compared to the other two cases. Therefore, the system time to finish one simulation of the Rhode Island nightclub scenario was the longest (more than 15 minutes) when using the A* algorithm, and the time that the computer spent on the 0.3 m^2 grid-based scenario was at least twice as long as the time spent on other scenarios and algorithms. Comparing the time to the 0.5 m^2 grid-based scenarios, the 0.3 m^2 grid-based Gothenburg dance hall scenario took 4.3-4.7 times longer to process, the 0.3 m^2 grid-based Rhode Island nightclub scenario took 3.4-6.9 times longer, and the 0.3 m^2 grid-based Hamlet chicken processing plant scenario took 4.3-8.0 times shorter.

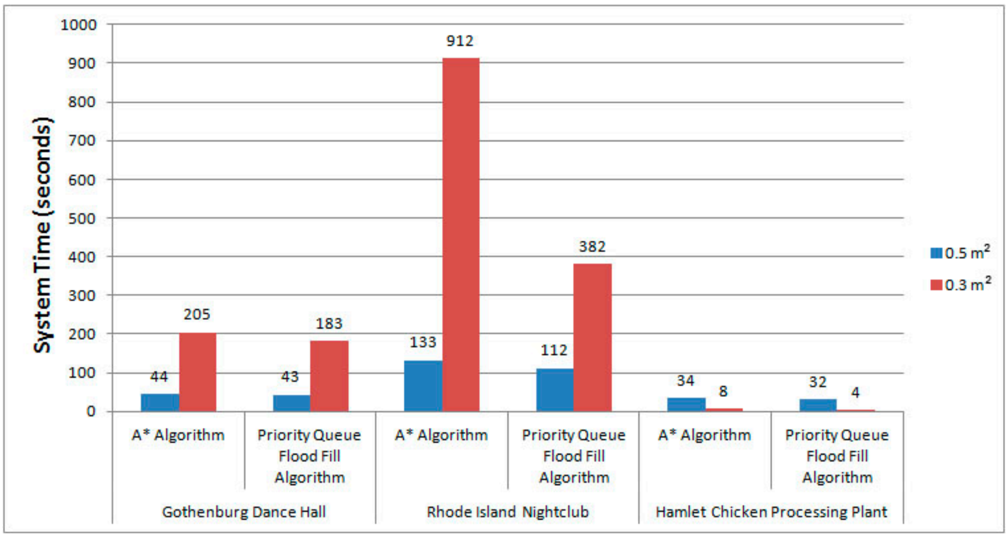


Figure 9-16 Average system run time that the computer spent on one simulation run using different navigation algorithms in each of the grid-based fire scenarios

9.3 The Influences of Parameters and Configuration Change

Section 8.2 demonstrated the results of the 0.5 m^2 grid-based scenarios using five main methods of analysis comprising tests of egress selection, evacuation time, the number of deaths and injuries, distribution of deaths and system run time, in order to validate the model. The section concluded that the Rhode Island nightclub scenario contains the most fire statistics and high similarity over the tests. The same tests were calculated for the 0.3 m^2 grid-based scenarios, and the comparisons between two grid sizes showed the decrease in the similarities. Therefore, this section explores different proposed scenarios based on the 0.5 m^2 grid-based Rhode Island nightclub layout in order to test what might happen if the model parameters and building configuration change.

Table 9-2 displays the parameters of the original model and five proposed scenarios for various variables including the number of pedestrian agents, kitchen area accessibility, fire location and building configuration.

Table 9-2 Parameters of the original and proposed 0.5 m^2 grid-based Rhode Island nightclub scenarios (the highlighted cells represent the differences to the original model)

	Number of Pedestrian Agents	Kitchen Area Accessibility	Fire Location	Building Configuration
Original Model	458	Blocked	Platform	Origin (Figure 7-12)
Scenario 1	458	Available	Platform	Origin
Scenario 2	458	Blocked	Storage Room	Origin
Scenario 3	258	Blocked	Platform	Origin
Scenario 4	258	Available	Platform	Origin
Scenario 5	258	Available	Platform	Modify entryway in the main door area (Figure 9-18)

The original model was the 0.5 m^2 grid-based Rhode Island nightclub scenario, used for the main tests in Section 8.2. The parameters of the Rhode Island nightclub scenario were developed according to the information provided in the fire report (Section 6.2). Therefore, 458 pedestrian agents were set up in the building, a fire/smoke agent started on the platform and the kitchen area and exit were blocked to avoid access during the evacuation (Section 7.2.1). Five scenarios are proposed by changing the parameters or modifying the building configuration.

Scenario 1 allows pedestrian agents to access the kitchen area and use the kitchen exit to escape during the fire evacuation, because 12 people (mostly employees) actually evacuated through this exit in the fire disaster (Section 6.4.2). Scenario 2 changes the location of the fire origin from the platform to a storage room (the innermost room), which is displayed as the white grid in Figure 9-17, in order to examine whether evacuation movement is influenced by the spread of fire and smoke. Scenario 3 reduces the number of pedestrian agents to 258 based on the permitted volume of the building (see Section 6.4.2). Scenario 4 simulates 258 pedestrian agents in the building without any restricted area to examine what happens if they follow the fire safety code. To avoid crowds becoming stuck in the corridor near the front entrance, Scenario 5 modifies the entryway to change the pedestrian flow of the environment (Figure 9-18).

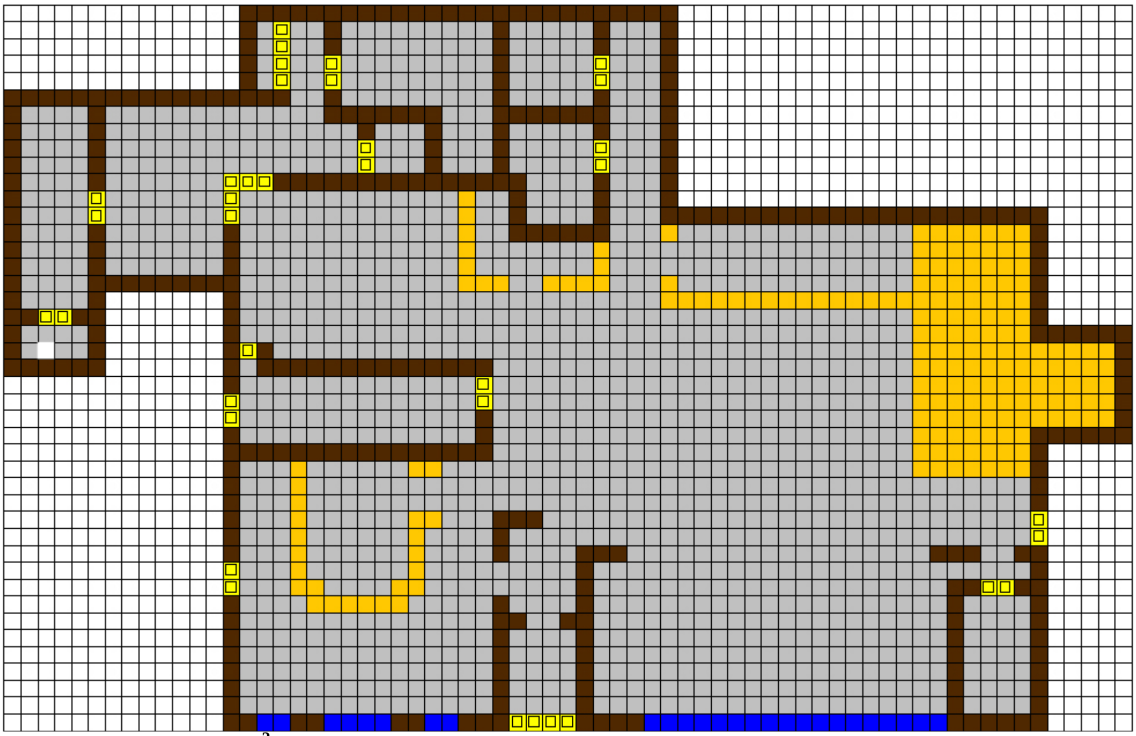


Figure 9-17 A 0.5 m^2 grid-based map of the Rhode Island nightclub with a fire started from a storage room

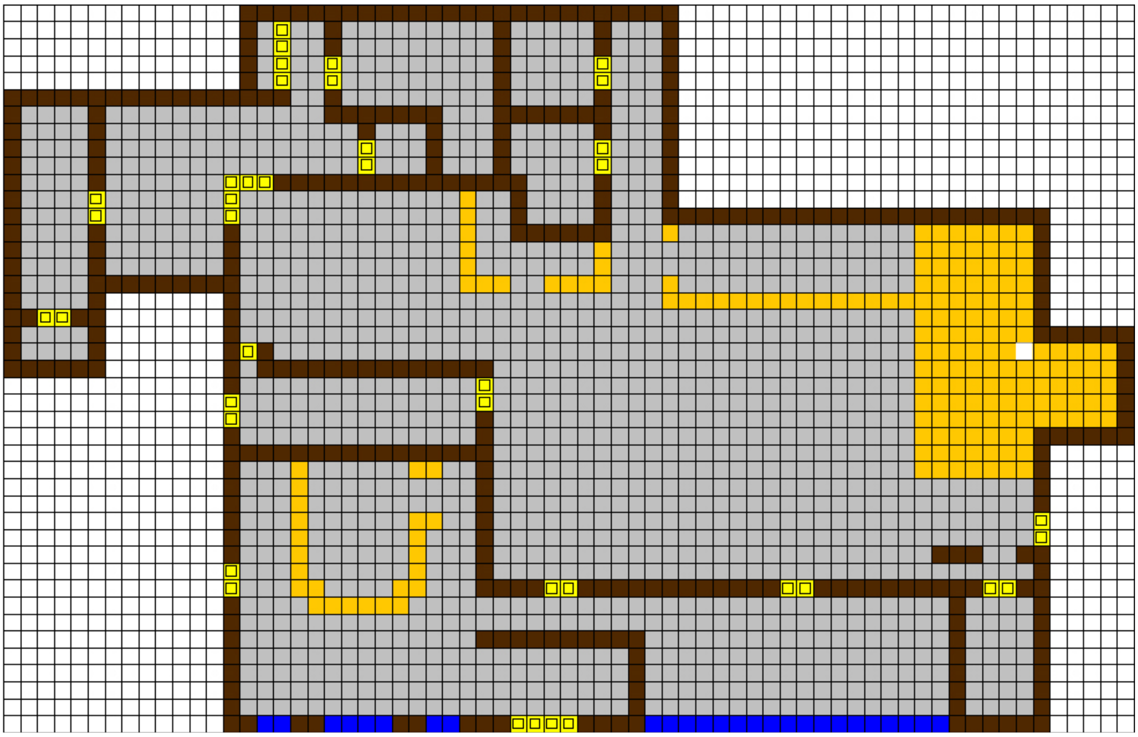


Figure 9-18 Modified entryway around the main entrance of the Rhode Island nightclub building

The following subsections display the results of the different proposed scenarios.

9.3.1 Test 1: Egress Selection

The original Rhode Island nightclub scenario blocked the kitchen area because it was restricted to customers during the fire evacuation. Therefore, potential egress routes including the front entrance, platform exit, main bar exit and windows were the four approaches used by pedestrian agents to evacuate in scenarios 2 and 3. In addition to the four egress selections, the kitchen exit was available for pedestrian agents in scenarios 1, 4, and 5. The results of the number of pedestrian agents who evacuated through each exit or window are displayed in Figure 9-19.

The results show a significant number of pedestrian agents evacuated through the kitchen exit in scenarios 1, 4, and 5 (Figure 9-19c), meaning that more occupants could have survived had they known where the exit was located in the actual fire disaster. In these five scenarios, the front entrance, which attracted the largest group of evacuees (Figure 9-19a), remained the most commonly used exit compared to other exits. In addition, windows were also a popular egress route, used by the second highest number of pedestrian agents (Figure 9-19e), and the main bar side exit was used by the fewest pedestrian agents in these scenarios (Figure 9-19b).

The number of pedestrian agents who used the main entrance in scenario 2 was almost three times the numbers calculated in other scenarios. A potential reason was that scenario 2 relocated the fire's original location to an inner space of the building, leading more people to evacuate the building through exits in an order manner before the fire/smoke spread over the space. In addition to the front entrance, more pedestrians evacuated through the platform exit in scenario 2 (Figure 9-19d), so the usage of the platform exit increased when the fire was relocated.

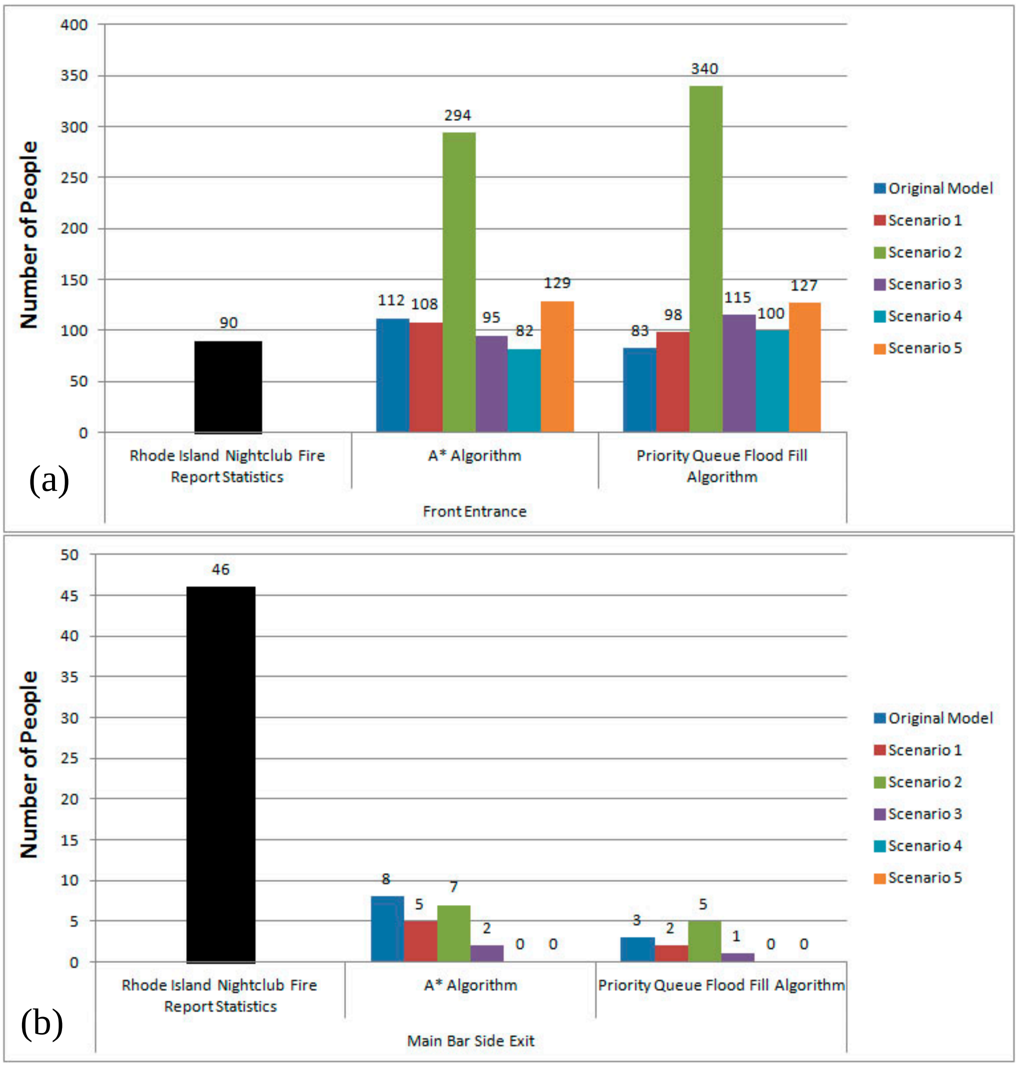


Figure 9-19 Number of pedestrian agents (median value of 500 runs) who evacuated through the (a) front entrance, (b) main bar side exit, (c) kitchen exit, (d) platform exit and (e) windows in the original and proposed 0.5 m^2 grid-based Rhode Island nightclub scenarios

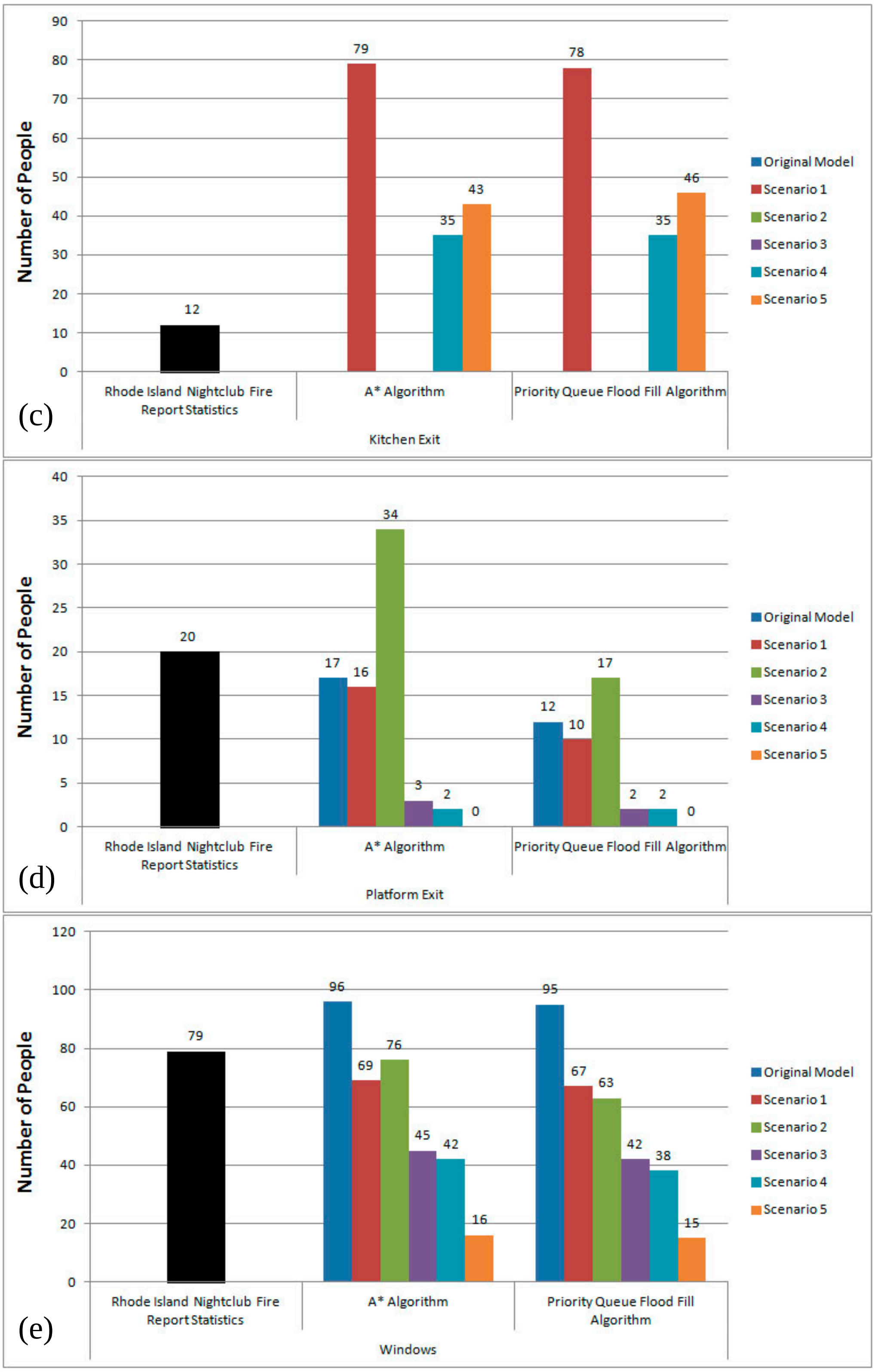


Figure 9-19 continued. Number of pedestrian agents (median value of 500 runs) who evacuated through the (a) front entrance, (b) main bar side exit, (c) kitchen exit, (d) platform exit and (e) windows in the original and proposed 0.5 m2 grid-based Rhode Island nightclub scenarios

9.3.2 Test 2: Evacuation Time

Figure 9-20 shows the evacuation time that pedestrian agents spent at each exit. A greater amount of time spent at one exit could represent either large numbers of pedestrian agents trying to evacuate through this exit or that it was the last potential exit they could use due to the spread of fire. For instance, occupants mainly used the front entrance to evacuate, so the evacuation time that people spent at the front entrance was always longer than other exits (Figure 9-20a). The evacuation time at the main bar side exit in scenario 2 was significantly greater than the times in other scenarios (Figure 9-20b), and this was potentially caused by the spread of fire, since the location of fire was changed to an inner storage area, forcing pedestrian agents to alter their evacuation directions. The change of fire location also influenced the platform exit. The fire that started on the platform blocked the exit within one minute, whereas pedestrian agents were still evacuating through this exit after three minutes in scenario 2 (Figure 9-20d). Overall, the evacuation time of the five scenarios was between three and four minutes.

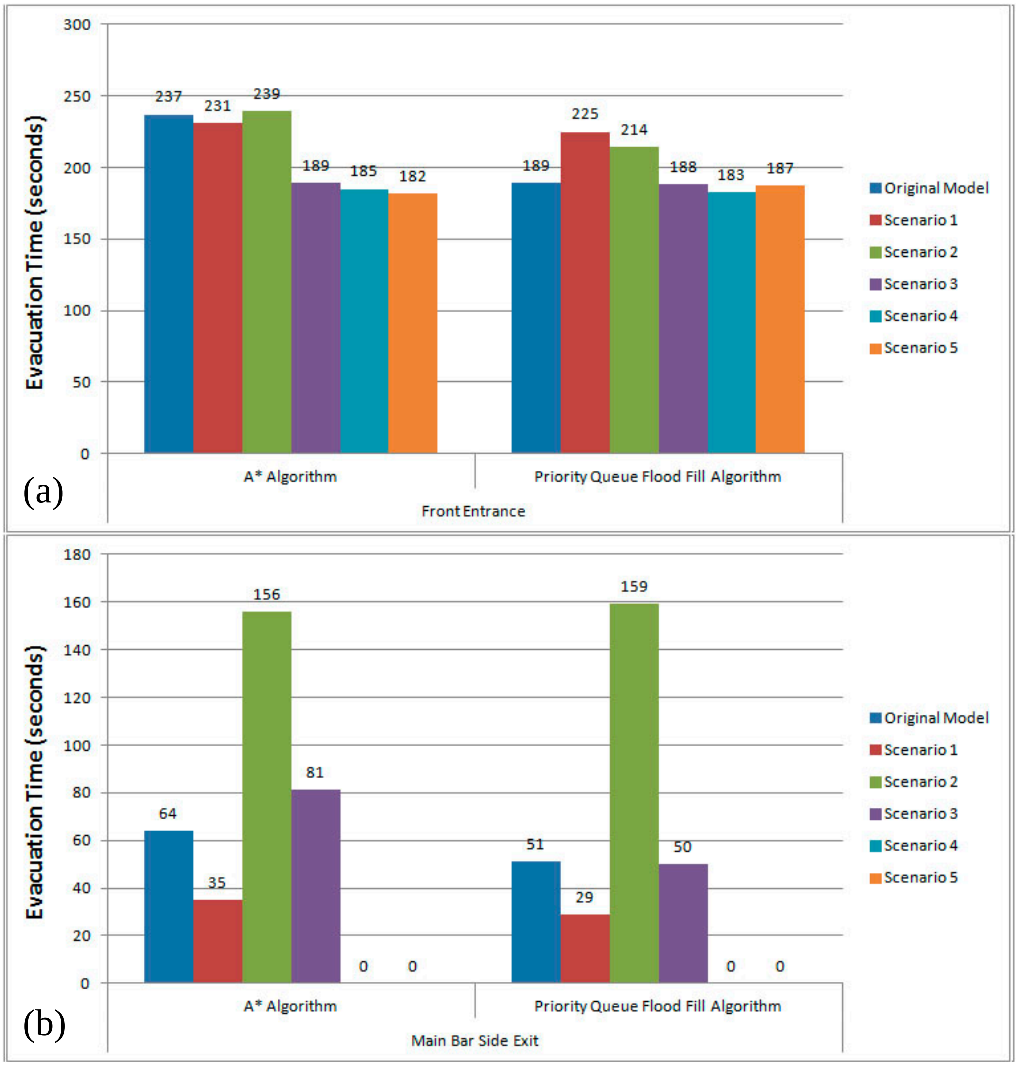


Figure 9-20 Evacuation time (median value of 500 runs) spent by evacuees agents when evacuating through the (a) front entrance, (b) main bar side exit, (c) kitchen exit, (d) platform exit and (e) windows in the original and proposed 0.5 m^2 grid-based Rhode Island nightclub scenarios

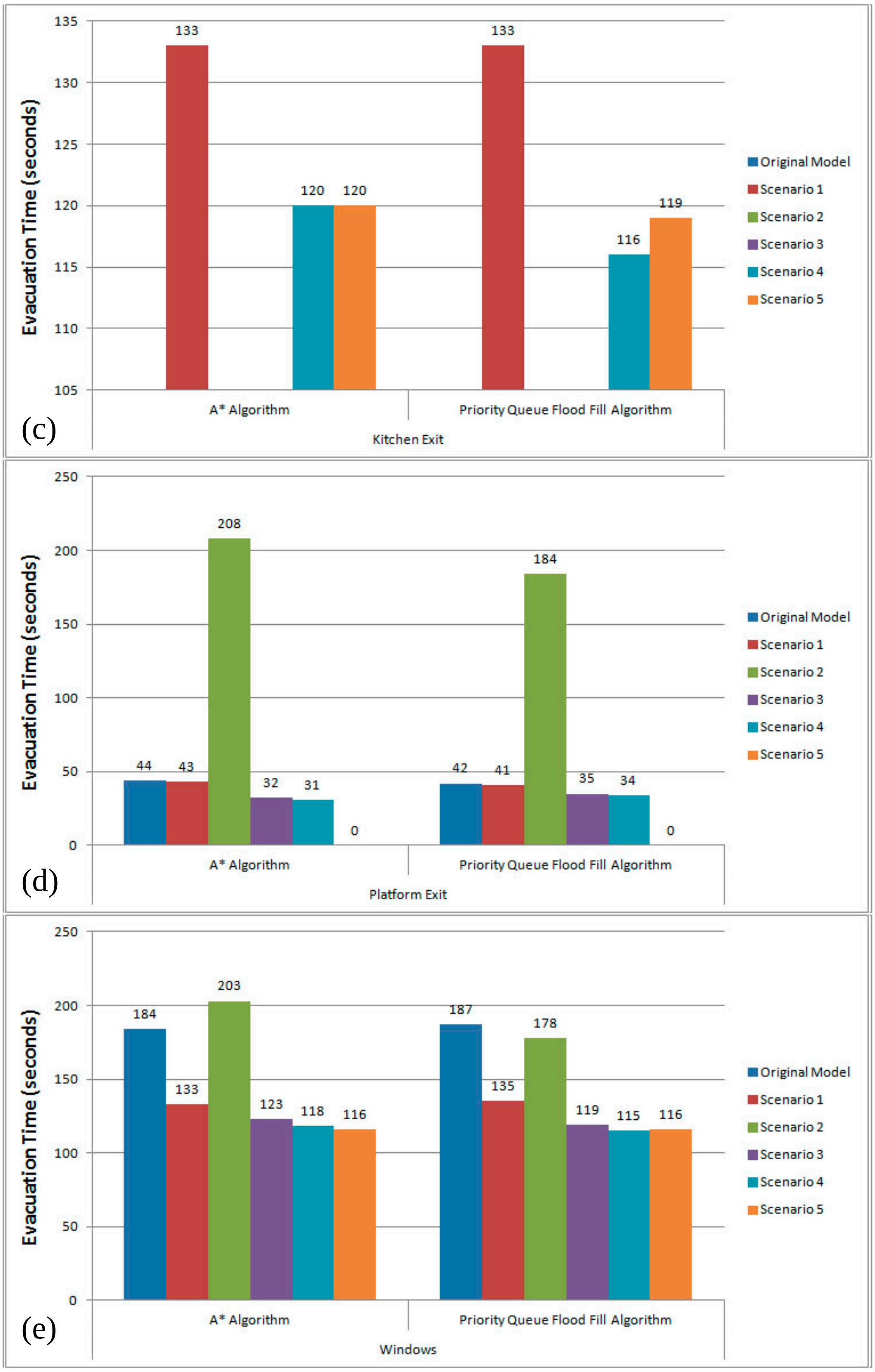


Figure 9-20 continued. Evacuation time (median value of 500 runs) spent by evacuees agents when evacuating through the (a) front entrance, (b) main bar side exit, (c) kitchen exit, (d) platform exit and (e) windows in the original and proposed 0.5 m2 grid-based Rhode Island nightclub scenarios

9.3.3 Test 3: Numbers of Deaths and Injuries

According to the numbers of deaths and injuries displayed in Figure 9-21, the five proposed scenarios simulated less deaths and injuries than the original 0.5 m^2 grid-based Rhode Island nightclub scenario. Scenario 1 allowed pedestrian agents to use the kitchen exit, so more pedestrian agents evacuated through the additional exit (see Figure 9-19c) and fewer people died inside the building (Figure 9-21a). Scenario 2 simulated on average 90% of the total pedestrian agents evacuated from the building (see Section 9.3.1), so the number of deaths that occurred in the scenario was less than 20. Scenarios 3 and 4 simulated less than half of the numbers of deaths and injuries that were in the original scenario, which might be caused by the reduction in the number of pedestrian agents. Scenario 5 changed the evacuation flow of the building, and the result shows a lower number of deaths when pedestrian agents evacuated in the modified configuration.

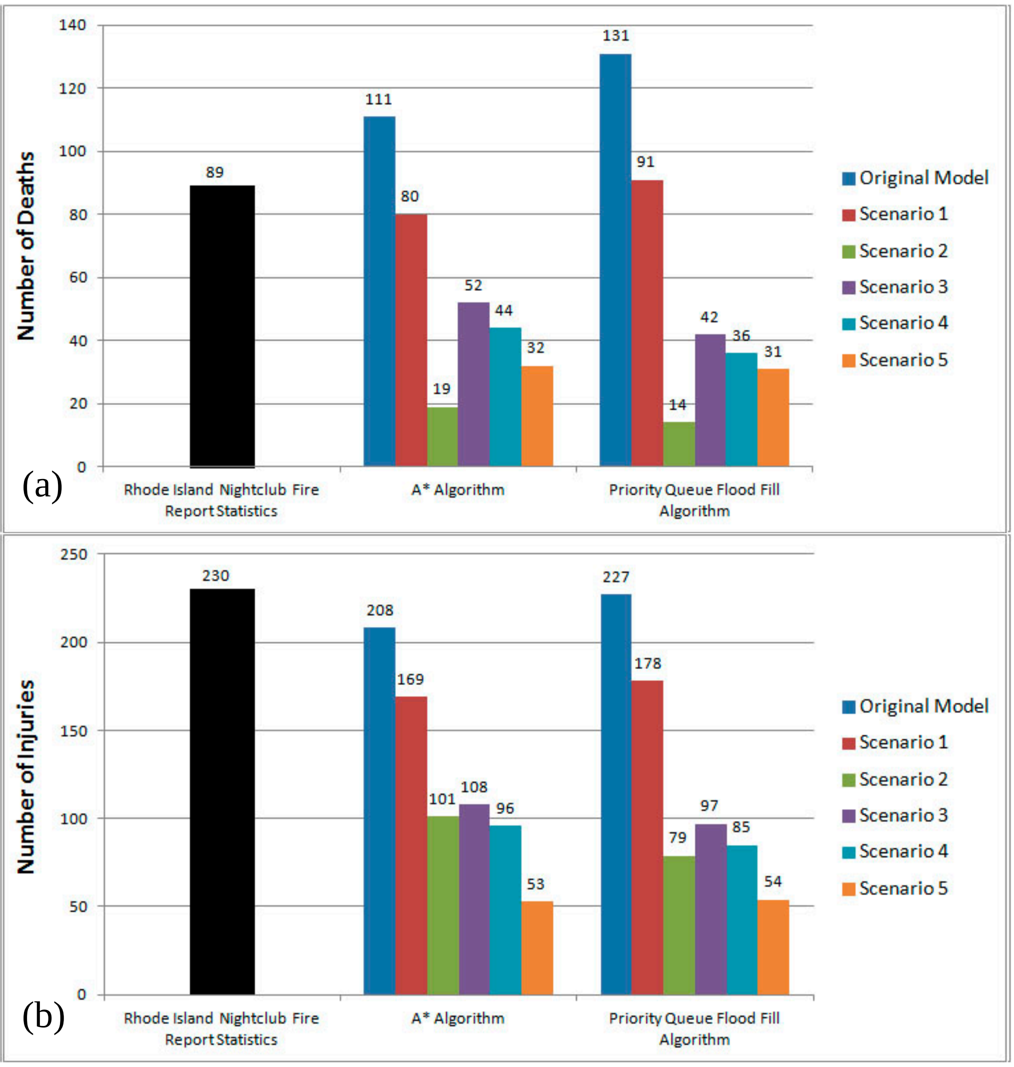


Figure 9-21 Number of (a) deaths and (b) injuries (median value of 500 runs) that occurred in the original and proposed 0.5 m^2 grid-based Rhode Island nightclub scenarios

9.3.4 Test 4: Distribution of Deaths

The decrease in the total number of deaths in each scenario (see Figure 9-21a) influenced the number of deaths in the main risk areas (front entrance and the Sunroom), which were the two highest groups of deaths in the actual fire disaster. The choropleth maps that show the distribution of deaths in the Rhode Island nightclub scenarios are displayed in Appendix E. Comparing the results of the proposed scenarios to the original scenario, fewer pedestrian agents died in the main risk areas (Figure 9-23a and e), but the number of deaths that were found inside the building in areas such as rooms and the storage area were about the same (Figure 9-23b and c). In addition, almost no pedestrian agents died in the Dart room (Figure 9-23d) in the proposed scenarios.

Scenario 5 modified the building configuration so the areas that were identified in the new configuration are displayed in Figure 9-22. The results that were simulated in scenario 5 were compared to the scenario 3 as well as scenario 4, because scenario 4 had the same parameters other than the building configuration, whereas scenario 3 had two parameter differences (kitchen area accessibility and building configuration). The number of deaths in the entryway (Region 1) decreased in the new building configuration (see Figure 9-23a) and other regions remained the same.

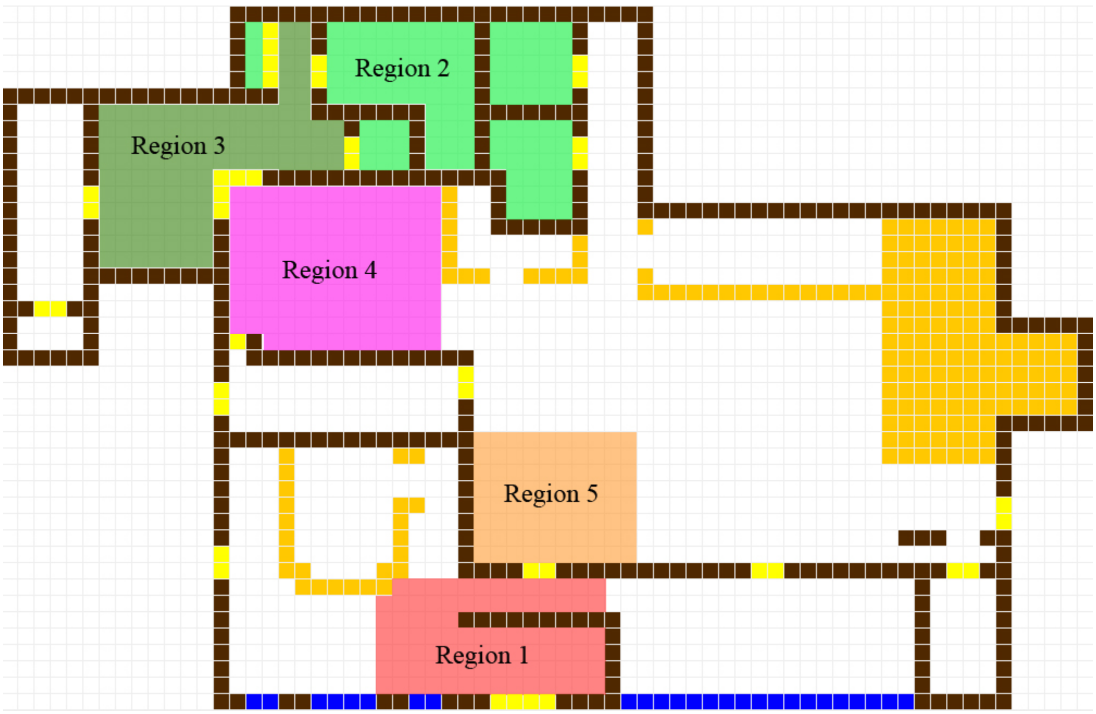


Figure 9-22 Region identification after modifying the entryway near the front entrance

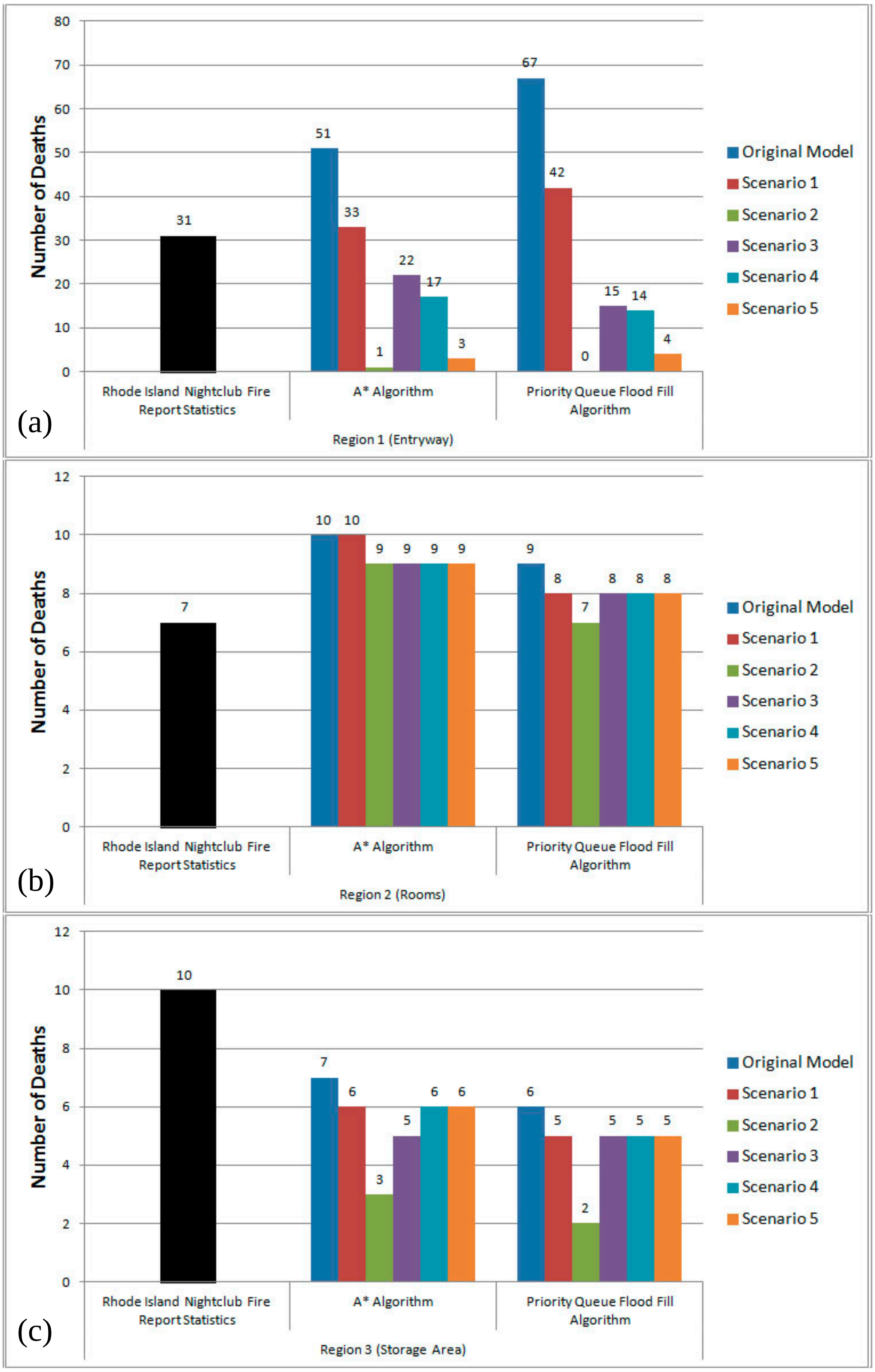


Figure 9-23 Number of deaths (median value of 500 runs) that occurred in the regions of (a) entryway, (b) rooms, (c) storage area, (d) Dart room, and (e) Sunroom in the original and proposed 0.5 m^2 grid-based Rhode Island nightclub scenarios

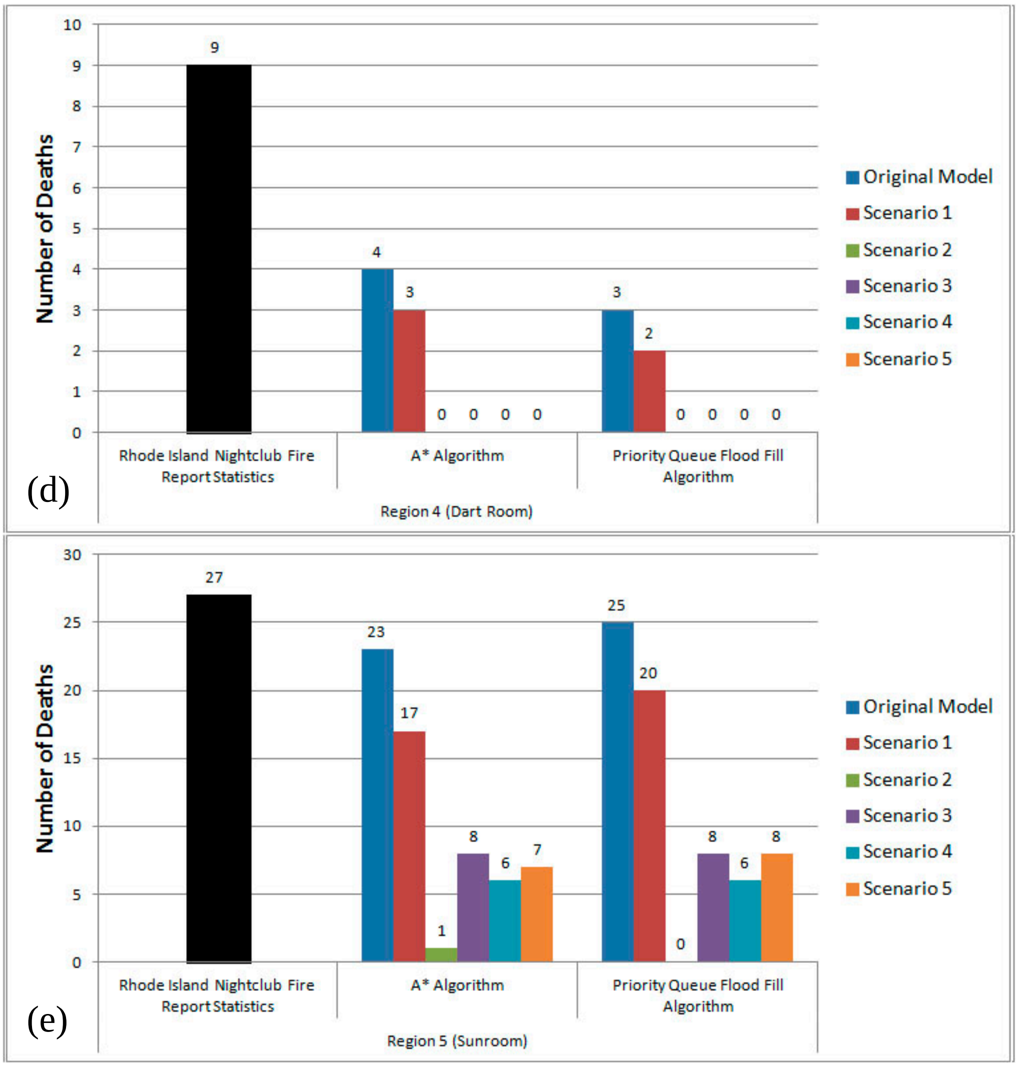


Figure 9-23 continued. Number of deaths (median value of 500 runs) that occurred in the regions of (a) entryway, (b) rooms, (c) storage area, (d) Dart room, and (e) Sunroom in the original and proposed 0.5 m2 grid-based Rhode Island nightclub scenarios

The number of deaths in each region was calculated as an occurrence rate (Figure 9-24). The two highest percentages of death occurrence rate in scenarios 1, 3, and 4 were similar to the original scenario, because about half of the deaths occurred in the entryway (Region 1) or the Sunroom (Region 5) closest to the front entrance (Figure 9-24a and e). In addition, the lowest number of deaths always occurred in the Dart room (Region 4) throughout the different scenarios (Figure 9-24d).

A significant different phenomenon occurred in scenario 2, as it simulated a small percentage of deaths around the main exit (Figure 9-24a) and a large percentage of deaths occurred inside the building (Figure 9-24b). Although the number of deaths in the rooms (Region 2) and the storage area (Region 3) were about the same in the original and five proposed scenarios (see Figure 9-23b and c), the percentages of deaths show significant differences between scenarios (Figure 9-24b and c).

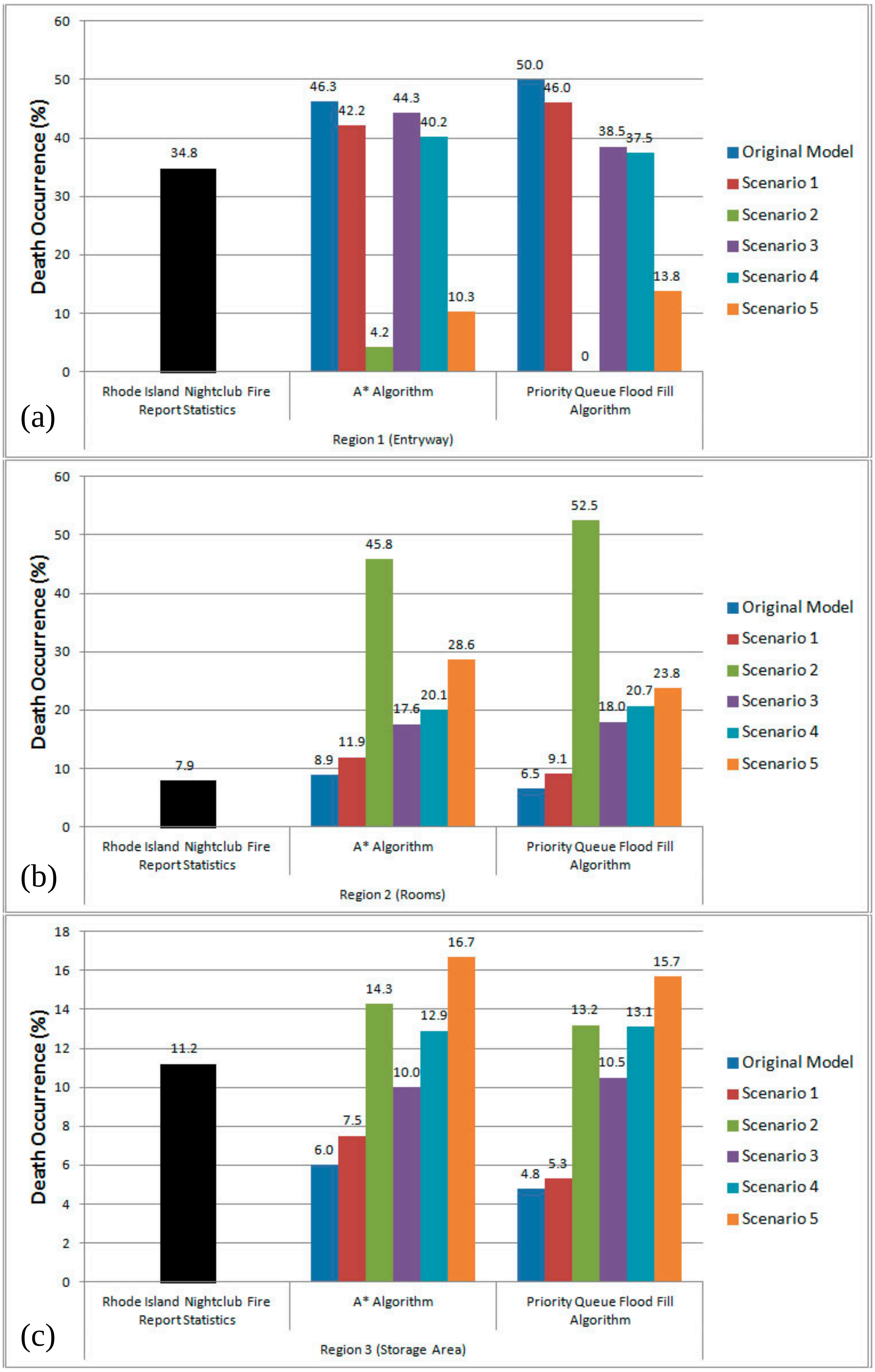


Figure 9-24 Percentage of death (median value of 500 runs) in the regions of (a) entryway, (b) rooms, (c) storage area, (d) Dart room and (e) Sunroom in the original and proposed 0.5 m^2 grid-based Rhode Island nightclub scenarios

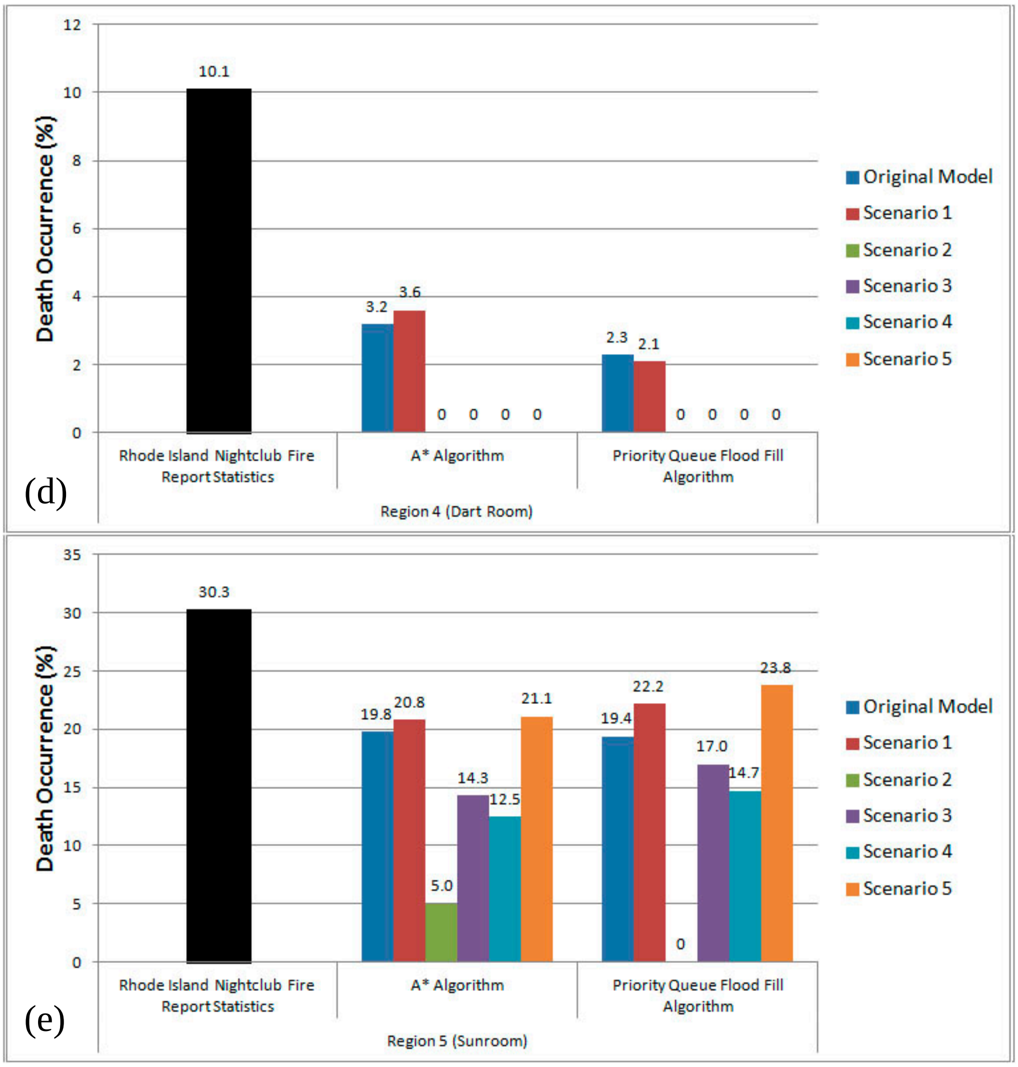


Figure 9-24 continued. Percentage of death (median value of 500 runs) in the regions of (a) entryway, (b) rooms, (c) storage area, (d) Dart room and (e) Sunroom in the original and proposed 0.5 m2 grid-based Rhode Island nightclub scenarios

9.3.5 Test 5: System Run Time

All these scenarios used the same system environment as the original model. The differences between each scenario are solely the reduced number of pedestrian agents (scenarios 3, 4 and 5), the two additional exit agents in the kitchen area (scenarios 1, 4 and 5), and the building configuration changes (scenario 5). Figure 9-25 shows the system run time for each scenario calculated from the 500 simulation runs. The results show the calculation times for various scenarios were less than the system time of the original model. In general, the model processing time calculated by the A* algorithm was longer than the Priority Queue Flood Fill algorithm.

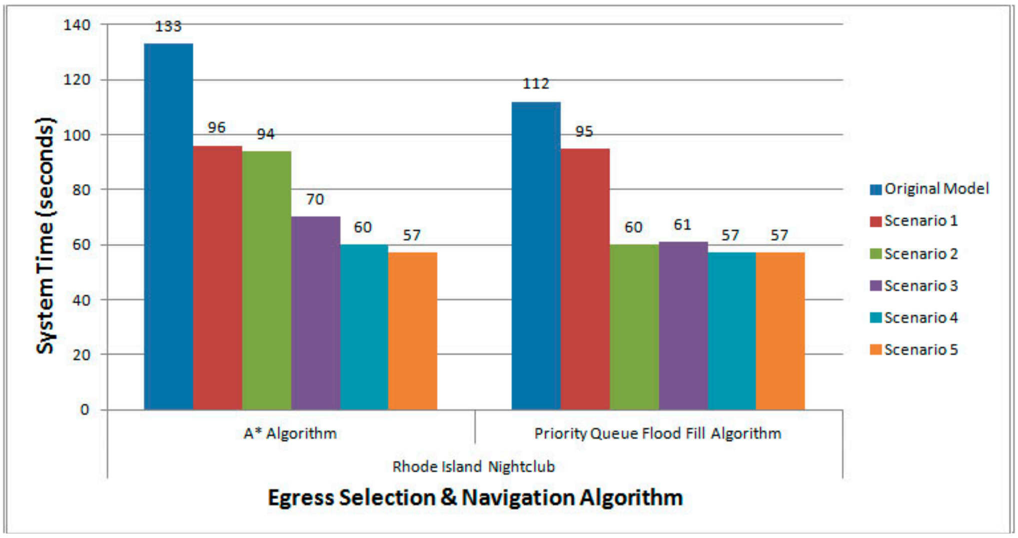


Figure 9-25 System run time (median value of 500 runs) that the computer spent on one simulation run for the original and proposed 0.5 m^2 grid-based Rhode Island nightclub scenarios

9.4 Chapter Summary

This chapter compared the results of the 0.3 m^2 and 0.5 m^2 grid-based scenarios by using five different tests. As noted, these five tests were designed to validate the evacuation model (Section 3.5), and comparisons with the actual disasters were made when statistics were available in the fire reports.

The total number of successful evacuees in the 0.3 m^2 grid-based scenario increased and most evacuated through the main exit. A potential reason of the increasing number of evacuees is that the smaller grid size created a greater capacity for exit. For example, the 1.5m wide exit represented three cells in the 0.5 m^2 grid-based scenario, and the number of cells in the exit increased to five in the 0.3 m^2 grid-based scenario. Therefore, the increase in the number of cells led to more people evacuating from the building in a short time, as it was considered that the number of pedestrian agents who could pass through the exit at the same time increased from three to five in the 0.3 m^2 grid-based scenario.

The evacuation flow in the 0.3 m^2 grid-based scenarios was generally faster than in the 0.5 m^2 grid-based scenarios, even if a greater number of pedestrian agents evacuated through one door. Therefore, the overall evacuation time for each 0.3 m^2 grid-based scenario was shorter than the time that was calculated in the 0.5 m^2 grid-based scenario. The potential safe evacuation times calculated in the 0.3 m^2 grid-based scenarios differed by a range of 4 to 98 seconds to the 0.5 m^2 grid-based scenarios.

All the numbers of deaths and injuries decreased in the 0.3 m^2 grid-based scenarios, causing all the percentages of similarities to decrease. According to the results, the 0.3

m^2 grid-based model cannot recreate the situations of the actual fire disaster in the Hamlet chicken processing plant scenario, and the 0.3 m^2 grid-based Gothenburg dance hall and Rhode Island nightclub scenarios resulted in different levels of similarities to the fire statistics, which means the model has a relatively low rate of accuracy. In addition, more low similarities were found in the results regarding the distribution of deaths than in the number of deaths in each evacuation scenario.

Table 9-3 summarises the percentages of similarities for each test (if applicable) in the 0.3 m^2 and 0.5 m^2 grid-based scenarios. In the Gothenburg dance hall scenarios, the 0.3 m^2 grid-based scenario simulated no deaths occurred in the corner (Region 3) and the bar area (Region 4), which accurately represented real life events and thus increased the similarity from 0% to 100%. This influences the total percentage of similarities, which the 0.3 m^2 grid-based scenario was considered better than the 0.5 m^2 grid-based.

In the Rhode Island nightclub scenarios, most of the similarities decreased in tests of the 0.3 m^2 grid-based scenario. In addition, the total percentages of similarities in the 0.3 m^2 grid-based scenario decreased by almost half in comparison to the total percentage of similarities in the 0.5 m^2 grid-based scenario. Therefore, the results of the 0.5 m^2 grid-based scenario were considered to be reasonably close to the reality of the situation, but the results of the 0.3 m^2 grid-based scenario were not.

The level of similarities in the number of deaths and injuries in the 0.3 m^2 grid-based Hamlet chicken processing plant scenario significantly decreased to zero as no deaths occurred in the simulation. Therefore, the percentage of similarity in the 0.3 m^2 grid-based scenario was calculated either 0% or 100% when comparing to the real fire statistics. In terms of the poor performance, it is established that the current configuration of this model did not provide a reasonable representation of the Hamlet chicken processing plant fire disaster.

In addition to the results that summarised in the table, the results of egress selection (the Gothenburg dance hall model and the Hamlet chicken processing plant model), evacuation time and system runtime were displayed in Section 9.2. According to the results calculated in the 0.5 m^2 and 0.3 m^2 grid-based scenarios, each fire scenario had a different quality of simulations when compared to the statistics from the fire reports. Overall, the A* algorithm calculated better results than the Priority Queue Flood Fill algorithm, and the 0.5 m^2 grid size was better representative of the human body than the 0.3 m^2 grid size, according to the total percentages of similarities.

Table 9-3 The percentages of similarities in terms of the comparisons between the simulation results of 0.5 m^2 and 0.3 m^2 grid-based scenarios and the fire report statistics

Validation	Test	Similarity			
		0.5 m^2		0.3 m^2	
		A*	PF	A*	PF
Gothenburg Dance Hall Scenario					
Accuracy	Number of Deaths	71.4	57.1	28.6	23.8
	Number of Injuries	85.0	84.4	62.8	76.1
	Number of Deaths in Region 1 (Corridor)	39.5	32.6	18.6	11.6
	Number of Deaths in Region 2 (Room)	20.0	25.0	35.0	45.0
	Number of Deaths in Region 3 (Corner)	0	0	0	100
	Number of Deaths in Region 4 (Bar Area)	0	0	100	100
	Percentage of Deaths in Region 1 (Corridor)	56.8	57.1	68.4	48.8
	Percentage of Deaths in Region 2 (Room)	28.4	40.4	68.5	2.8
	Percentage of Deaths in Region 3 (Corner)	0	0	0	100
	Percentage of Deaths in Region 4 (Bar Area)	0	0	100	100
Total Percentage of Similarities		301.0	296.6	481.9	608.1
Rhode Island Nightclub Scenario					
Realism	Number of Evacuees at Exit 1 (Front Entrance)	75.6	92.2	0	0
	Number of Evacuees at Exit 2 (Main Bar Side Exit)	17.4	6.5	2.2	2.2
	Number of Evacuees at Exit 3 (Platform Exit)	85.0	60.0	0	0
	Number of Evacuees at Windows	78.5	79.7	92.4	75.9
Accuracy	Number of Deaths	75.3	52.8	73.0	25.8
	Number of Injuries	90.4	98.7	73.9	40.4
	Number of Deaths in Region 1 (Entryway)	35.5	0	77.4	6.5
	Number of Deaths in Region 2 (Rooms)	57.1	71.4	0	100
	Number of Deaths in Region 3 (Storage Area)	70.0	60.0	80.0	70.0
	Number of Deaths in Region 4 (Dart room)	44.4	33.3	0	0
	Number of Deaths in Region 5 (Sunroom)	85.2	92.6	14.8	7.4
	Percentage of Deaths in Region 1 (Entryway)	67.0	56.3	93.7	27.3
	Percentage of Deaths in Region 2 (Rooms)	87.3	82.3	0	0
	Percentage of Deaths in Region 3 (Storage Area)	53.6	42.9	44.6	0
	Percentage of Deaths in Region 4 (Dart room)	31.7	22.8	0	0
	Percentage of Deaths in Region 5 (Sunroom)	65.3	64.0	18.8	34.7
Total Percentage of Similarities		989.3	915.5	570.8	390.2
Hamlet Chicken Processing Plant Scenario					
Accuracy	Number of Deaths	68.2	72.7	0	0
	Number of Injuries	53.7	53.7	0	0
	Number of Deaths in Region 1 (Front Entrance)	0	0	100	100
	Number of Deaths in Region 2 (Cooler)	0	0	0	0
	Number of Deaths in Region 3 (Rooms)	0	100	100	100
	Number of Deaths in Region 4 (Processing Room)	0	0	0	0
	Number of Deaths in Region 5 (Trim Room)	0	0	0	0
	Percentage of Deaths in Region 1 (Front Entrance)	0	0	100	100
	Percentage of Deaths in Region 2 (Cooler)	0	0	0	0
	Percentage of Deaths in Region 3 (Rooms)	0	100	100	100
	Percentage of Deaths in Region 4 (Processing Room)	0	0	0	0
	Percentage of Deaths in Region 5 (Trim Room)	0	0	0	0
Total Percentage of Similarities		121.9	326.4	400	400

Among the three study cases, the results from the Rhode Island nightclub scenario were identified as the best outcomes, and were closest to the fire statistics provided by the actual fire report. Therefore, five proposed scenarios were designed based on the Rhode Island nightclub scenario to identify the impact of parameters change. Table 9-4 shows the comparisons of similarity between the proposed scenarios and the original scenario. The colour of each cell in the table represents the decrease (light grey) or increase (dark grey) in percentage of similarity. The cells without colour represent no changes or unable to compare with the original scenario.

These scenarios were simulated according to various parameters and the building configuration was changed in order to understand what might happen if the following situations were to occur.

(1) The kitchen area and exit are available to all the occupants.

(2) Fire starts at a different location.

(3) The number of people is within the permitted volume for the building.

(4) Both the number of people and the building follow the fire safety code.

(5) The building configuration near the main entrance is different.

Scenario 1 demonstrated results similar to those that occurred in the original scenario; however, the results of other scenarios, which were designed to understand how people react under different conditions of fire and building configurations, show significant differences to the original scenario. In scenarios 2 to 5, most of the pedestrian agents evacuated of the building, so fewer deaths occurred in the building. However, the deaths that occurred in these scenarios tended to take place in the inner building rather than near the exits.

The results of simulation outcomes were displayed by case study as well as by validation test. The next chapter compares the overall results across the different navigation algorithms and fire scenarios. Subsequently, an optimal configuration for the model is identified in terms of the validation of realism, accuracy and processing speed.

Table 9-4 A summary of each comparison between the original model and different scenarios, using colour to represent the decrease or increase of similarity

Rhode Island Nightclub Model	0.5 m^2 Model		Scenario 1		Scenario 2		Scenario 3		Scenario 4		Scenario 5	
	A*	PF	A*	PF	A*	PF	A*	PF	A*	PF	A*	PF
Number of People Used Exit 1 (Front Entrance)	75.6	92.2	80.0	91.1	0	0	94.4	72.2	91.1	88.9	56.7	58.9
Number of People Used Exit 2 (Main Bar Side Exit)	17.4	6.5	10.9	4.3	15.2	10.9	4.3	2.2	0	0	0	0
Number of People Used Exit 3 (Kitchen Exit)	N/A	N/A	0	0	N/A	N/A	N/A	N/A	0	0	0	0
Number of People Used Exit 4 (Platform Exit)	85.0	60.0	80.0	50.0	30.0	85.0	15.0	10.0	10.0	10.0	0	0
Number of People Used Windows	78.5	79.7	87.3	84.8	96.2	79.7	57.0	53.2	53.2	48.1	20.3	19.0
Number of Deaths	75.3	52.8	89.9	97.8	21.3	15.7	58.4	47.2	49.4	40.4	36.0	34.8
Number of Injuries	90.4	98.7	73.5	77.4	43.9	34.3	47.0	42.2	41.7	37.0	23.0	23.5
Number of Deaths in Region 1 (Front Entrance)	35.5	0	93.5	64.5	3.2	0	71.0	48.4	54.8	45.2	9.7	12.9
Number of Deaths in Region 2 (Rooms)	57.1	71.4	57.1	85.7	71.4	100	71.4	85.7	71.4	85.7	71.4	85.7
Number of Deaths in Region 3 (Storage Area)	70.0	60.0	60.0	50.0	30.0	20.0	50.0	50.0	60.0	50.0	60.0	50.0
Number of Deaths in Region 4 (Dart Room)	44.4	33.3	33.3	22.2	0	0	0	0	0	0	0	0
Number of Deaths in Region 5 (Sunroom)	85.2	92.6	63.0	74.1	3.7	0	29.6	29.6	22.2	22.2	25.9	29.6
Death Occurrence in Region 1 (Front Entrance)	67.0	56.3	78.7	67.8	12.1	0	72.7	89.4	84.5	92.2	29.6	39.7
Death Occurrence in Region 2 (Rooms)	87.3	82.3	49.4	84.8	0	0	0	0	0	0	0	0
Death Occurrence in Region 3 (Storage Area)	53.6	42.9	67.0	47.3	72.3	82.1	89.3	93.8	84.8	83.0	50.9	59.8
Death Occurrence in Region 4 (Dart Room)	31.7	22.8	35.6	20.8	0	0	0	0	0	0	0	0
Death Occurrence in Region 5 (Sunroom)	65.3	64.0	68.6	73.3	16.5	0	47.2	56.1	41.3	48.5	69.6	78.5

Increase	Decrease

10. Summary and Discussion of Evacuation Simulation

Introduction and Background	Contents of Evacuation Modelling	Developing Research Questions	Developing an Evacuation Model	Simulation Outcomes	Discussion	Conclusion and Further Work
Ch. 1	Ch. 2	Ch. 3	Ch. 4, 5 and 6	Ch. 7, 8 and 9	Ch. 10	Ch. 11

10.1 Introduction

The previous three chapters presented the results from a set of evacuation simulations. Chapter 7 introduced the process for evaluation of the preliminary model using the human behaviour and location of victims that occurred in the Gothenburg dance hall and the Rhode Island nightclub evacuation scenarios. Chapter 8 presented the main simulation outputs from the 0.5 m^2 grid-based scenarios. Chapter 9 displayed the results from the 0.3 m^2 grid-based scenarios and five proposed scenarios of the Rhode Island nightclub scenario, created by changing various parameters to understand the influences of different conditions.

This chapter offers an overall comparison of the three fire evacuation scenarios, using statistical comparisons and identifying common patterns across the three different case studies. In addition, the influences of modelling assumptions and the situations that were not simulated in the models are discussed. Next, the model is validated and evaluated for its suitability as an optimal approach for each of the realisation or prediction purposes. Finally, the results of the Gothenburg dance hall and the Rhode Island nightclub scenarios are compared to existing evacuation models developed by other researchers.

10.2 Statistical comparisons of the two navigation algorithms

Two modified navigation algorithms (the A* algorithm and Priority Queue Flood Fill algorithm) were developed to simulate pedestrian evacuation movement in the model (Section 6.3). Results such as the number of deaths, injuries, or evacuees vary in every simulation run, so an average number was calculated in each case to represent the simulation results over the multiple runs. To identify whether two sets of results that were calculated by different navigation algorithms are statistically different from one another, the Wilcoxon signed ranks analysis was used to examine the equality of the results for overall simulation outcome. The Wilcoxon signed ranks test is a non-parametric statistical test used to identify if there is a significant difference between two groups, determining whether two median values are sufficiently different from each other without requiring any assumptions about the shape of distribution.

In order to use statistical comparisons to compare the results from two independent groups, the hypotheses for a two-sided test are: a null hypothesis that the medians of the two algorithms are the same, and an alternative hypothesis that the medians of the two algorithms are not the same. In addition, a 95% confidence interval for the difference was chosen to estimate the range of values. Therefore, the null hypothesis is rejected if the median value is out of the range of the difference allowed by the confidence interval. Table 10-1 summarises all the statistical tests in 0.5 m^2 and 0.3 m^2 grid-based scenarios.

Table 10-1 Wilcoxon signed ranks tests on the equality of two outcomes from the A* algorithm and the Priority Queue Flood Fill algorithm

	0.5m^2	**0.3m^2**
Gothenburg Dance Hall Scenario		
Number of Evacuees at Exit 1 (Main Exit)	Rejected	Rejected
Number of Evacuees at Exit 2 (Emergency Exit)	Rejected	Rejected
Number of Evacuees at Windows	Rejected	Rejected
Evacuation Time at Exit 1 (Main Exit)	Rejected	Rejected
Evacuation Time at Exit 2 (Emergency Exit)	Rejected	Rejected
Evacuation Time at Windows	Rejected	Rejected
Number of Deaths	Rejected	Rejected
Number of Injuries	Accepted	Rejected
Number of Deaths in Region 1 (Corridor)	Rejected	Rejected
Number of Deaths in Region 2 (Room)	Rejected	Rejected
Number of Deaths in Region 3 (Corner)	Rejected	Rejected
Number of Deaths in Region 4 (Bar Area)	Rejected	Rejected
Percentage of Deaths in Region 1 (Corridor)	Accepted	Rejected
Percentage of Deaths in Region 2 (Room)	Rejected	Rejected
Percentage of Deaths in Region 3 (Corner)	Rejected	Rejected
Percentage of Deaths in Region 4 (Bar Area)	Rejected	Rejected
System Run Time	Rejected	Rejected
Total (17 tests)	Accepted: 2 (11.8%) **Rejected: 15 (88.2%)**	Accepted: 0 (0%) **Rejected: 17 (100%)**
	0.5m^2	**0.3m^2**
Rhode Island Nightclub Scenario		
Number of Evacuees at Exit 1 (Front Entrance)	Rejected	Rejected
Number of Evacuees at Exit 2 (Main Bar Side Exit)	Rejected	Rejected
Number of Evacuees at Exit 3 (Platform Exit)	Rejected	Accepted
Number of Evacuees at Windows	Accepted	Rejected
Evacuation Time at Exit 1 (Front Entrance)	Rejected	Rejected
Evacuation Time at Exit 2 (Main Bar Side Exit)	Rejected	Rejected
Evacuation Time at Exit 3 (Platform Exit)	Rejected	Accepted
Evacuation Time at Windows	Accepted	Rejected
Number of Deaths	Rejected	Rejected
Number of Injuries	Rejected	Rejected

Number of Deaths in Region 1 (Entryway)	Rejected	Rejected
Number of Deaths in Region 2 (Rooms)	Rejected	Rejected
Number of Deaths in Region 3 (Storage Area)	Rejected	Rejected
Number of Deaths in Region 4 (Dart room)	Rejected	Rejected
Number of Deaths in Region 5 (Sunroom)	Rejected	Rejected
Percentage of Deaths in Region 1 (Entryway)	Rejected	Rejected
Percentage of Deaths in Region 2 (Rooms)	Rejected	Rejected
Percentage of Deaths in Region 3 (Storage Area)	Rejected	Rejected
Percentage of Deaths in Region 4 (Dart room)	Rejected	Rejected
Percentage of Deaths in Region 5 (Sunroom)	Accepted	Rejected
System Run Time	Rejected	Rejected
Total (21 tests)	Accepted: 3 (14.3%) **Rejected: 18 (85.7%)**	Accepted: 2 (9.5%) **Rejected: 19 (90.5%)**
	$0.5m^2$	**$0.3m^2$**
Hamlet Chicken Processing Plant Scenario		
Number of Evacuees at Exit 1 (Main Entrance)	Accepted	Rejected
Number of Evacuees at Exit 2 (Side Exit)	Accepted	Rejected
Number of Evacuees at Exit 3 (Break Room Exit)	Accepted	Rejected
Number of Evacuees at Exit 4 (Equipment Exit)	Rejected	Accepted
Number of Evacuees at Two Exits (apart from the main building)	Accepted	Accepted
Evacuation Time at Exit 1 (Main Entrance)	Accepted	Rejected
Evacuation Time at Exit 2 (Side Exit)	Accepted	Rejected
Evacuation Time at Exit 3 (Break Room Exit)	Accepted	Rejected
Evacuation Time at Exit 4 (Equipment Exit)	Rejected	Rejected
Evacuation Time at Two Exits (apart from the main building)	Accepted	Rejected
Number of Deaths	Accepted	Rejected
Number of Injuries	Accepted	Rejected
Number of Deaths in Region 1 (Front Entrance)	Accepted	Rejected
Number of Deaths in Region 2 (Cooler)	Accepted	Rejected
Number of Deaths in Region 3 (Rooms)	Rejected	Rejected
Number of Deaths in Region 4 (Processing Room)	Accepted	Accepted
Number of Deaths in Region 5 (Trim Room)	Accepted	Accepted
Percentage of Deaths in Region 1 (Front Entrance)	Accepted	Rejected
Percentage of Deaths in Region 2 (Cooler)	Accepted	Accepted
Percentage of Deaths in Region 3 (Rooms)	Rejected	Accepted
Percentage of Deaths in Region 4 (Processing Room)	Accepted	Accepted
Percentage of Deaths in Region 5 (Trim Room)	Accepted	Accepted
System Run Time	Rejected	Rejected
Total (23 tests)	**Accepted: 18 (78.3%)** Rejected: 5 (21.7%)	Accepted: 8 (34.8%) **Rejected: 15 (65.2%)**

A great number of rejections according to the results of Wilcoxon signed ranks analysis, so the results from the two navigation algorithms were significantly different from each other. The main reason for the differences is that pedestrian agents behave differently in terms of the complex interactions between pedestrian, door and fire/smoke agents under the two navigation algorithms. The A* algorithm calculates a route from an individual location to a final destination every time a pedestrian agent makes a decision, and a pedestrian agent decides an egress route based on the pre-calculated potential table when using the Priority Queue Flood Fill algorithm. Therefore, pedestrian agents face different conditions and make different decisions during their different movements at different times. These results are used to underpin the selection of an optimal approach for the simulation of evacuation movement in the model (Section 10.4).

10.3 Reviewing the Evacuation Model

Section 9.2 compared the results between the 0.5 m^2 and 0.3 m^2 grid-based scenarios as an individual case. Where the fire statistics were available, the simulation results were compared to the statistics and the findings were calculated in terms of the percentage of similarity. Section 9.4 summarised these comparison results in a table detailing the cases of the Gothenburg dance hall, the Rhode Island nightclub, and the Hamlet chicken processing plant (Table 9-3).

The following subsections introduce an overview of the evacuation model based on the analysis of results and observations during the simulations. Section 10.3.1 concludes the overall comparisons and the common patterns across the tests of the three evacuation scenarios. When developing the model, a number of assumptions were made to simulate complex human behaviour and recreate the scenarios of the fire disaster. The potential influence of these assumptions on the results is discussed in Section 10.3.2. Finally, Section 10.3.3 presents the situations that were excluded from the model due to a lack of information or factors that were not recorded in the fire reports, but were important to evacuation modelling.

10.3.1 Patterns that are common to the evacuation simulations

Five patterns that are common across the three scenarios are identified below, according to the analysis of the results from the visualisation of simulations, the statistical analysis of results and the graphs of death distributions.

1) <u>*The model predicts more accurate results for the number of deaths and injuries than for other tests*</u>

The percentages of similarities were influenced by the assumption that the statistics in the fire reports faithfully represent the actual fire disaster (Section 10.3.2), when in fact an actual fire disaster only represents one random fire case in real life. However, the model simulates specific potential outcomes that are identified as being very close to the outcome of an incident. According to the percentages of similarities in Table 9-3, the best representative results were identified as the number of deaths and injuries because of the high percentages. In contrast, the results of the other comparisons show many low percentages of similarities, especially in the Hamlet chicken processing plant scenario. Additionally, when the number of deaths was classified into smaller regions, the accuracy of results decreased.

2) <u>Deaths mostly occurred near the main entrance</u>

Section 8.2.4 and Appendix D display the distribution of deaths in the 0.5 m^2 and 0.3 m^2 grid-based scenarios. In the choropleth maps, the distribution of deaths was classified into different levels of risk based on the natural breaks classification. As Figure 8-14 and Figure 8-18 show, high risk areas occurred near the entrance to the 0.5 m^2 grid-based Rhode Island nightclub and the Hamlet chicken processing plant scenarios, whereas this significantly changed from the main entrance to an inner space in the case of the Gothenburg dance hall scenario (Figure 8-10). Similar patterns are found in the 0.3 m^2 grid-based scenarios. However, choropleth maps that classify risk levels as individual grids cannot represent the risk level of a region. Therefore, death occurrences were calculated in terms of the classified regions (see Figure 9-11, Figure 9-13 and Figure 9-15). According to the percentages of deaths that occurred in each region, people mostly perished in the place that was closest to the main entrance in most scenarios, similar to the choropleth maps displayed.

3) <u>Windows were considered to be another main egress route</u>

The evacuation decisions of a pedestrian agent are dictated by the model in the following percentages: evacuate through the main entrance (100%) before panic occurs, then escape through the main entrance (40%), emergency exits (20%) and windows (15%), or find a room to hide (15%), stay at the current location and consider what to do next (10%). According to the definition, the model should simulate most pedestrian agents evacuating through the main entrance and then the emergency exits. However, the simulation results show the number of evacuees who used the emergency exits was far lower than the number of people who used windows (Figure 9-1 and Figure 9-2). The results were influenced by the number of exits and windows, the interactions of pedestrian agents and fire/smoke agents, and the restriction of exit agents. For example, the emergency exit in the Gothenburg dance hall scenarios was blocked after the fire/smoke agents arrived, so pedestrian agents could only evacuate through the main door and windows. In the Rhode Island nightclub scenarios, the main entrance and windows were most frequently used compared to the rest of the egress routes, since fewer than 10% of pedestrian agents evacuated through the alternative exits (the main bar side exit and the platform exit). In addition to the main entrance, windows were considered to be one of the main egress routes, although a low percentage of evacuation decisions was assigned to pedestrian agents.

4) *Pedestrian agents became stuck when moving to different directions*

Situations where pedestrian agents become stuck and delay evacuation processes are caused by too many pedestrian agents trying to move in different directions at the same time. This situation was found in the Gothenburg dance hall scenarios; pedestrian agents were stuck at the corner for a long time, because most were moving from the dance hall to the corridor and some were moving towards the windows. At the same time, pedestrian agents who were trying to move in and out of the room also influenced the evacuation flow outside the door near the corner (Figure 7-6). In the Rhode Island nightclub scenarios, many pedestrian agents were trying to search for alternative routes, but became stuck in the entryway near the main door. The same situation occurred in the Hamlet chicken processing plant scenarios; deaths only occurred around the main entrance when pedestrian agents were trying to move in different directions, otherwise all of the pedestrian agents would have evacuated safely.

5) *Navigation algorithms restricted pedestrian movement*

The A* algorithm and the Priority Queue Flood Fill algorithm were the two navigation algorithms used in the evacuation model. Although these algorithms were modified to allow multi-paths (Section 6.3), in real life people would not always walk in the way the algorithms calculated. For example, pedestrian agents were programmed to follow the shortest path (diagonal distance), so a restricted zone (red cells) in which agents would never walk during the simulations developed around corners (Figure 10-1); this only changed if they shifted aside after queuing for a long time, as designed in the model (Section 5.4.7).

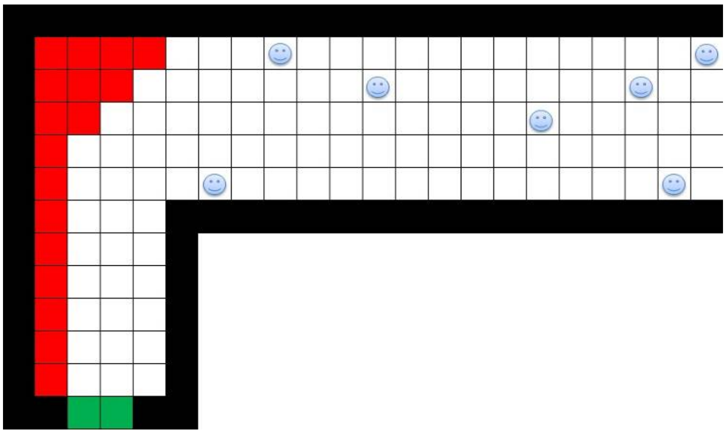


Figure 10-1 Potential pedestrian movement towards the exit (green cells); red cells represent the restricted movement zone

10.3.2 Assumptions made for evacuation simulation

Section 4.4 described a number of assumptions for simulating human behaviour in the model, and additional assumptions were made in Chapter 5 during the development of agents in order to recreate the situations that might occur in actual fire disasters. However, it is impossible to fully simulate the human mind in a computer-based simulation, and using fire reports to develop human behaviours may influence the simulation outcomes. Therefore, this section introduces the assumptions in the model that potentially influenced the results.

Human minds and activities are complex and unpredictable, because they are influenced by an individual's characteristics and experiences of life. Therefore, the model started by simulating the common evacuation behaviours that were identified from the twenty studied fire reports. These common behaviours were developed by excluding a number of situations that might occur in real life. Table 10-2 lists some of the situations and the potential influences of the assumptions.

Table 10-2 Potential influences caused by the assumptions made for evacuation simulation

Assumptions in the Model	Real Life Situations	Potential Influences
Building layout was based on the building plan in the fire reports. All single doors were designed as 0.8m wide.	• The width of doors is different than that specified in the building code. • The transcript of a manually drawn building plan can easily identify issues.	• Evacuation flow. • Building scale.
Pedestrian agents are randomly spread over the space.	• People would stay at a specific location for their own purposes.	• Overall evacuation time. • Evacuation movement.
Children and the elderly might attend a nightclub.	• Children are restricted and few elderly people attend nightclubs.	• Overall evacuation time.
Pedestrian agents move towards the main entrance as their first priority egress route.	• People might evacuate through the nearest or the most familiar exit.	• Uneven usage of exits. • Evacuation movement. • Overall evacuation time.
All pedestrian agents can reach the windows.	• Windows might be installed at higher positions. • Human height or other conditions may mean people cannot reach them.	• Usage of windows. • Overall evacuation time.
Pedestrian agents who escape through windows will be rescued by fire fighters and become injured.	• Some people jump and are hurt or die. • Some people escape without becoming injured.	• The number of injuries. • No deaths occur if people evacuate through windows.
Pedestrian agents who decide to hide in a room will remain in the room until they die or are rescued.	• People might leave the room according to the situations. • Evacuation decisions are based on individual characteristics, experiences, and knowledge. • People might be influenced by other people inside the room.	• An increase in the number of deaths.
A pedestrian agent changes his egress route when he becomes impatient while queuing behind others for a long time	• Individual decisions change at any time; for example, when people "see" crowds at the front. • Some people might stay in the queue.	• Overall evacuation time.
Pedestrian agents can see the status of their destination from any location, including behind an obstacle.	• People cannot see the current status before the target appears in their visual range.	• Evacuation movement. • Overall evacuation time.
Fire alarm is sounded at the same time as the fire starts.	• There is a delay time between the fire starting and the detector detecting heat/smoke.	• The time when people discover the fire, which is the time that pedestrian agents switch to panic mode in the model. • Evacuation movement. • Overall evacuation time.

Table 10-2 continued. Potential influences caused by the assumptions made for evacuation simulation

Assumptions in the Model	Real Life Situations	Potential Influences
All pedestrian agents start evacuating when the fire alarm sounds.	• People do pre-evacuation activities. • Delay of evacuation.	• Overall evacuation time.
All pedestrian agents change to "panic mode" at the same time (but people can actually panic or display calm behaviour) after hearing about the fire from the first witness.	• People cannot pass messages to all others in a short time because of distance.	• Evacuation movement. • Pedestrian walking speed. • Evacuation decision.
Pedestrian agents will faint or die at the scene if they inhale a volume of smoke that is too great for their capacity.	• The type of fire is unknown, and the fire creates different smoke conditions. • People take action to avoid smoke.	• The time when a person dies.
Fire fighters will randomly rescue people who have already fainted, allowing other survivors to keep evacuating.	• Fire fighters enter the fire scene from exits or windows, so they rescue people as soon as they discover one.	• The time when a person is rescued.
Pedestrian agents have unlimited visual distance.	• People cannot see very clearly beyond a certain distance, depending on their eyesight. • Visual range is restricted by smoke.	• The time the fire is discovered. • Evacuation movement. • Overall evacuation time.
Pedestrian agents will turn around to check what is happening behind them, and some will not see the fire even if they are close to the hazard.	• People can feel the heat and smell the burning around them.	• The location of the first witness. • The time that people start to panic.
Pedestrian agents who decide to hide in a room will hide at a place closest to a wall.	• People often hide under/in furniture or just stay in the room.	• The distribution of people who are hiding inside the room.
Pedestrian walking speed will be influenced by the number of evacuees at each door.	• Walking speed is influenced by other people around them, not by the number of people behind them.	• Evacuation movement. • Evacuation flow.
Egress capability of a door is calculated by dividing the total number of pedestrian agents by the number of exit agents	• According to the guidebook by Ching and Winkel (2012), the main exit should be able to accommodate 50% of the occupant load of the space, and the second means of exits are sized to handle the remaining 50% of the occupant load.	• Evacuation flow
Doors are self-closing and are not tested fire doors.	• The type of doors influences the spread of fire. • The gap between the floor and door influences the spread of smoke.	• The time a door holds the smoke.

The important findings from the investigation of the influence of assumptions are summarised as follows. Firstly, fire reports do not always provide accurate information, which might have influenced the design of the building configuration, the identification of risk areas and the comparisons of the results and fire statistics. For example, the building configuration in the model was based on the original building scale provided in the fire reports, but in fact some building plans were manually recorded by hand drawing and some information regarding the size of the scale was lost (the Hamlet chicken processing plant, see Figure 6-22). In addition, the distribution of deaths was classified by regions of the building on a floor map, but the locations of deaths in the fire reports were roughly drawn on a floor map (the Rhode Island nightclub fire, see Figure 6-20) or mentioned in text (the Gothenburg dance hall fire, see Section 6.4.1) and provided unclear boundaries. This might influence the comparisons of the results and the fire statistics in the distribution of deaths test.

The evacuation time was influenced by many assumptions made in the model. The model designed a fixed evacuation process from the start of the simulation to the point at which all the remaining pedestrian agents perish in terms of the four stages displayed in Figure 5-1. However, different fire disasters have different evacuation procedures, including the time at which people discover the fire, start evacuating and evacuate safely, and also the point when others faint, are rescued or die at the scene. Therefore, the safe evacuation time of a building calculated in the model is only useful as a safety reference.

In addition to the evacuation timeline, egress selection in the model, which shows the movement of a pedestrian agent evacuating from the current location to the final destination, changed during the evacuation according to the assumptions made. Other factors such as pedestrian walking speed, evacuation flow and the distribution of deaths were also influenced by these assumptions.

In addition to the modelling assumptions discussed above, a postulation was made when comparing the simulation results to the fire statistics, namely that the statistics in the fire reports echo the facts of the actual fire disaster. The question *"do fire statistics from one report represent any fire disaster that could happen in the same building?"* arose, because a disaster can be influenced by people, time, weather, location and many other conditions. In other words, the outcome of a fire disaster would be different even if repeated fires occurred at the same location with the same group of people. Green

(1998) also points out that every disaster is unique, and the level of actual threat to life and various situations that occur in the environments make each disaster somewhat different to the others. Therefore, the actual fire disaster should be considered to be a random fire disaster rather than a fixed fact; thus, more samples of the same fire disaster are required for data analysis. However, it is impossible for another fire event to take place with the same group of people evacuating from the same building under the same conditions. Therefore, comparisons between the simulation results and the fire statistics are mainly used to examine how closely the can model recreate the actual evacuation phenomena and thus validate the realism and accuracy of the model.

10.3.3 Situations which were excluded from the model

A limited number of behaviours and situations were selected and developed in the evacuation model. Two of the main reasons to exclude elements from the model were the lack of information provided in the fire reports and limited knowledge about human behaviour or fire events. The following four situations were excluded from the model, and potential reasons and influences are discussed below.

1) Building configurations were designed without furniture or decoration

Furniture (objects) is distributed for specific human activities. Using the studied nightclubs (the Gothenburg dance hall and the Rhode Island nightclub) as an example, tables and seats were organised for patrons to rest and drink, lighting equipment was set up for the stage and dance hall, and equipment was placed in the kitchen area to prepare food and drinks. In addition, boxes, cupboards and other decorations were found at the scene, according to the photography from the fire reports (Comeau and Duval, 2000; Grosshandler *et al*., 2005). Another fire location, the Hamlet chicken processing plant, had many machines for producing chicken products and dense smoke was caused by the fire burning the machines in the processing room (Yates, 1991). However, the distribution of objects that restricted the movement of occupants during an evacuation was not normally recorded on a floor map.

If the model had included furniture in the scenarios, it would have increased the complexity of calculations in terms of the number of obstacles, and might have slowed down the evacuation process of the pedestrian agents, resulting in more deaths in the building due to the obstacles restricting people's movement.

2) The time of the day is not considered in the model

The time at which the fire takes place might influence human activities and evacuation behaviour, especially at night. For example, people might be less aware of fire while they are sleeping at night and thus spend longer in the pre-evacuation period. In addition, a fire occurring at night might cut off lights and restrict human visual distance. This situation would confuse individual directions of movement and cause people to take a longer time to find an egress route out of a building.

If the model simulated the time of the day, the movement speed of pedestrian agents who evacuated during the night might decrease due to the lighting conditions, and thus result in longer evacuation times or more deaths due to confusion during navigation.

3) The type of fire and smoke varies and is difficult to predict

Fire is usually accompanied by smoke, which is the main cause of death at the scene of a fire and should thus be carefully considered in the simulation. According to NFPA 921 (2011), smoke quickly grows dark under the conditions of low-oxygen or post-flashover, and black smoke is often produced when the fire burns plastics or ignitable liquids. However, it is difficult to predict the type of fire due to the complexity of the environment and the human activities that might cause a fire to happen.

If the model accurately simulates the type of fire and smoke, the health conditions of pedestrian agents should change in order to simulate people inhaling different levels of smoke. For example, people might faint quickly once they inhale dense smoke, so more deaths would occur in this situation.

4) The spread of fire and smoke is based on many conditions and is difficult to predict

The spread of fire and smoke can be influenced by various conditions in the building such as the heat source, rate of burn, materials, temperature and humidity. Furthermore, it is also influenced by the two previous points, the distribution of objects and the type of fire/smoke. It is difficult to assess all of these factors accurately due to the lack of information provided in the fire reports.
If the model accurately simulates the type of fire and smoke, pedestrian agents might move differently in terms of the spread of fire and smoke in the environment. Therefore, pedestrian agents might use different exits to evacuate or die at a different location.

5) People not only sense surroundings by seeing, but also hearing, smelling or feeling

The model is developed with an unlimited human visual range for pedestrian agents to figure out the location of fire and smoke (Section 5.4.3). In reality, people might have a limited visual distance due to the distribution of objects, restrictions caused by visual angles, and distance between the current location and the target. In addition, people can feel what is happening around them by sensing their surroundings. For example, people can smell something burning, hear the crackling sounds made by the fire, or feel the heat in the air, all of which will cause them to notice the unusual phenomenon. Therefore, people take action such as investigating the environment after they sense these conditions.

If the model enabled pedestrian agents to notice the fire by different methods, agents might become aware of the fire earlier before smoke spreads into the space. Therefore, pedestrian agents would experience a faster evacuation process, which would decrease the number of deaths occurring in the disaster.

10.4 Validating the Evacuation Model

Different types of evacuation model (realisation and prediction) have different requirements to achieve their goals. Section 3.5 introduced the criteria for evacuation modelling, including realism, accuracy and processing speed, in order to identify an evacuation modelling type for the model. Therefore, five tests were designed to validate its realism, accuracy and processing speed, as explained in Section 8.2. However, a lack of statistics was found in the fire reports, so no standard evacuation time can be compared with the simulation results, and the number of evacuees can only be compared in the case of the statistics from the Rhode Island nightclub fire report.

According to the results in Table 9-3, the percentages of similarities are classified into six different levels in order to validate the level of realism, accuracy and processing speed of the evacuation model. Six levels are defined as negligible (0%), very low (0%－20%), low (20%－40%), medium (40%－60%), high (60%－80%), very high (80%－100%). Table 10-3 displays the level of representation in terms of the similarity level, for validating realism and accuracy, and the standard simulation time, for validating processing speed.

Table 10-3 The level of representation in terms of the similarity level and the standard simulation time

		$0.5m^2$ Grid Size Similarity (%)		$0.3m^2$ Grid Size Similarity (%)	
		A*	**PF**	**A***	**PF**
Gothenburg Dance Hall Scenario					
Accuracy: Number of Deaths and Injuries (2 tests)		Very High: 1 High: 1 Medium: 0 Low: 0 Very Low: 0 Negligible: 0	Very High: 1 High: 0 Medium: 1 Low: 0 Very Low: 0 Negligible: 0	Very High: 0 High: 1 Medium: 0 Low: 1 Very Low: 0 Negligible: 0	Very High: 0 High: 1 Medium: 0 Low: 1 Very Low: 0 Negligible: 0
Level of Representation		**High**	**High**	**Moderate**	**Moderate**
Accuracy: Distribution of Deaths	By Number (4 tests)	Very High: 0 High: 0 Medium: 0 Low: 2 Very Low: 0 Negligible: 2	Very High: 0 High: 0 Medium: 0 Low: 2 Very Low: 0 Negligible: 2	Very High: 1 High: 0 Medium: 1 Low: 1 Very Low: 0 Negligible: 1	Very High: 2 High: 0 Medium: 1 Low: 0 Very Low: 1 Negligible: 0
	By Occurrence (4 tests)	Very High: 0 High: 0 Medium: 1 Low: 1 Very Low: 0 Negligible: 2	Very High: 0 High: 0 Medium: 2 Low: 0 Very Low: 0 Negligible: 2	Very High: 1 High: 2 Medium: 0 Low: 0 Very Low: 0 Negligible: 1	Very High: 2 High: 0 Medium: 1 Low: 0 Very Low: 1 Negligible: 0
Level of Representation		**Low**	**Low**	**Moderate**	**High**
Processing speed		44 seconds	43 seconds	205 seconds	183 seconds
Level of Representation		**Slow**	**Slow**	**Slow**	**Slow**
Rhode Island Nightclub Scenario					
Realism: Egress Selection (4 tests)		Very High: 1 High: 2 Medium: 0 Low: 0 Very Low: 1 Negligible: 0	Very High: 1 High: 1 Medium: 1 Low: 0 Very Low: 1 Negligible: 0	Very High: 1 High: 0 Medium: 0 Low: 0 Very Low: 1 Negligible: 2	Very High: 0 High: 1 Medium: 0 Low: 0 Very Low: 1 Negligible: 2
Level of Representation		**High**	**Moderate**	**Low**	**Low**
Accuracy: Number of Deaths and Injuries (2 tests)		Very High: 1 High: 1 Medium: 0 Low: 0 Very Low: 0 Negligible: 0	Very High: 1 High: 0 Medium: 1 Low: 0 Very Low: 0 Negligible: 0	Very High: 0 High: 2 Medium: 0 Low: 0 Very Low: 0 Negligible: 0	Very High: 0 High: 0 Medium: 1 Low: 1 Very Low: 0 Negligible: 0
Level of Representation		**High**	**High**	**High**	**Moderate**
Accuracy: Distribution of Deaths	By Number (5 tests)	Very High: 1 High: 1 Medium: 2 Low: 1 Very Low: 0 Negligible: 0	Very High: 1 High: 1 Medium: 1 Low: 1 Very Low: 0 Negligible: 1	Very High: 0 High: 2 Medium: 0 Low: 0 Very Low: 1 Negligible: 2	Very High: 1 High: 1 Medium: 0 Low: 0 Very Low: 2 Negligible: 1
	By Occurrence (5 tests)	Very High: 1 High: 2 Medium: 1 Low: 1 Very Low: 0 Negligible: 0	Very High: 1 High: 1 Medium: 2 Low: 1 Very Low: 0 Negligible: 0	Very High: 1 High: 0 Medium: 1 Low: 0 Very Low: 1 Negligible: 2	Very High: 0 High: 0 Medium: 0 Low: 2 Very Low: 0 Negligible: 3
Level of Representation		**Moderate**	**Moderate**	**Low**	**Low**
Processing speed		133 seconds	112 seconds	912 seconds	382 seconds
Level of Representation		**Slow**	**Slow**	**Slow**	**Slow**

Table 10-3 continued. The level of representation in terms of the similarity level and the standard simulation time

		$0.5m^2$ Grid Size Similarity (%)		$0.3m^2$ Grid Size Similarity (%)	
		A*	**PF**	**A***	**PF**
Hamlet Chicken Processing Plant Scenario					
Accuracy: Number of Deaths and Injuries		Very High: 0 High: 1 Medium: 1 Low: 0 Very Low: 0 Negligible: 0	Very High: 0 High: 1 Medium: 1 Low: 0 Very Low: 0 Negligible: 0	Very High: 0 High: 0 Medium: 0 Low: 0 Very Low: 0 Negligible: 2	Very High: 0 High: 0 Medium: 0 Low: 0 Very Low: 0 Negligible: 2
Level of Representation		**High**	**High**	**Low**	**Low**
Accuracy: Distribution of Deaths	By Number (5 tests)	Very High: 0 High: 0 Medium: 0 Low: 0 Very Low: 0 Negligible: 5	Very High: 1 High: 0 Medium: 0 Low: 0 Very Low: 0 Negligible: 4	Very High: 2 High: 0 Medium: 0 Low: 0 Very Low: 0 Negligible: 3	Very High: 2 High: 0 Medium: 0 Low: 0 Very Low: 0 Negligible: 3
	By Occurrence (5 tests)	Very High: 0 High: 0 Medium: 0 Low: 0 Very Low: 0 Negligible: 5	Very High: 1 High: 0 Medium: 0 Low: 0 Very Low: 0 Negligible: 4	Very High: 2 High: 0 Medium: 0 Low: 0 Very Low: 0 Negligible: 3	Very High: 2 High: 0 Medium: 0 Low: 0 Very Low: 0 Negligible: 3
Level of Representation		**Low**	**Low**	**Low**	**Low**
Processing speed		34 seconds	32 seconds	8 seconds	4 seconds
Level of Representation		**Slow**	**Slow**	**Moderate**	**Moderate**

The test of egress selection was established to judge the realism of the model. In the Rhode Island nightclub scenario, four egress choices, including the front entrance, the main bar side exit, the platform exit and windows, were available to all the pedestrian agents during the evacuation. Section 9.2.1 discussed the number of pedestrian agents who evacuated though each exit or window in the 0.5 m^2 and 0.3 m^2 grid-based scenarios. The 0.5 m^2 grid-based Rhode Island nightclub scenarios, using A* algorithms, were considered to be highly realistic due to the many high percentages of similarities that were identified, and the 0.3 m^2 grid-based Rhode Island nightclub scenarios were considered to meet a low level of realism.

The test of the numbers of deaths and injuries were used to validate the accuracy of the evacuation model. In these different scenarios, a high representation of accuracy was identified in all the 0.5 m^2 grid-based evacuation scenarios and the 0.3 m^2 grid-based Rhode Island nightclub scenario (A* algorithm). In contrast, a low representation of accuracy was identified in the 0.3 m^2 grid-based Hamlet chicken processing plant scenarios. The rest were identified as having moderate representations of accuracy.

The test of the distribution of deaths was also used to validate the accuracy of the evacuation model. The results show a low level of representation in the 0.5 m^2

grid-based Gothenburg dance hall scenarios and all the Hamlet chicken processing plant scenarios. In the Rhode Island nightclub scenarios, the 0.5 m^2 grid-based scenarios were identified as being moderately representative and all the 0.3 m^2 grid-based scenarios had a low level of representation of accuracy in the model.

Finally, the system run time test was used to examine processing speed. According to the definition, a fast processing speed is less than one second and slow response times are longer than 15 seconds (Section 3.5). The models that are used for training purposes especially require an immediate response time (less than one second) to reflect the interaction in real time. According to the results, all the calculations made in different scenarios of the model, except the 0.3 m^2 grid-based Hamlet chicken processing plant scenarios, were identified as having a slow representation of processing speed.

Based on the validation results, each combination of navigation algorithms and grid sizes was assigned to a modelling purpose, realisation or prediction if applicable. As noted in Section 1.2, *realisation* recreates existing scenarios to avoid similar disasters in the same environment and *prediction* simulates potential situations that might happen in a proposed building. The levels of realism, accuracy and processing speed for each type of model were displayed in Table 3-3, and Table 10-4 shows the validation results and the most suitable type for each of the combinations in the model.

Table 10-4 Selecting a suitable model type in terms of the level of each validation

Grid Size and Navigation Algorithm	Level of Each Validation	Model Type
0.5 m^2 grid-based A* algorithm	Realism: High Accuracy (number of deaths and injuries): High Accuracy (distribution of deaths): Low Processing speed: Slow	Prediction and Realisation
0.5 m^2 grid-based Priority Queue Flood Fill algorithm	Realism: Moderate Accuracy (number of deaths and injuries): High Accuracy (distribution of deaths): Low Processing speed: Slow	Prediction
0.3 m^2 grid-based A* algorithm	Realism: Low Accuracy (number of deaths and injuries): Moderate Accuracy (distribution of deaths): Low Processing speed: Slow	None
0.3 m^2 grid-based Priority Queue Flood Fill algorithm	Realism: Low Accuracy (number of deaths and injuries): Moderate Accuracy (distribution of deaths): Low Processing speed: Slow	None

As noted in Section 1.2, this thesis aims to develop a high level of realism and a high level of accuracy for the prediction type of the evacuation model. The results shows that the model that calculates pedestrian movement by using the A* algorithm in the 0.5 m^2 grid-based scenarios can be used for the purposes of prediction and realisation. In addition, the model that uses the Priority Queue Flood Fill algorithm in the 0.5 m^2 grid-based scenarios can be used for the purpose of prediction. The results obtained could form the basis of future work to improve evacuation strategies and prevent serious casualties from happening in future events as well as recreate existing or past scenarios in order to understand the current issues or what happened in the disasters. In conclusion, this research has developed a model that is suitable for "prediction" and "realisation" purposes.

The realisation type of evacuation modelling simulates the current facts or past scenarios in order to understand the issues in the environment, and the prediction type of modelling simulates which might happen in future events. Therefore, the simulations of the Gothenburg dance hall, the Rhode Island nightclub and the Hamlet chicken processing plant fire scenarios were examples of the realisation type of evacuation model. The five proposed scenarios that were modified from the standard Rhode Island nightclub scenario (Section 9.3) were examples of the prediction type of evacuation model. According to the results from the proposed scenarios that were calculated by the A* algorithm on the 0.5 m^2 grid-base, scenario 2 simulated the fewest deaths when the fire started in the inner building with the same number of occupants and the same conditions in the building.

10.5 A Comparison with Other Simulation Methods

As noted in the previous section, the model was identified as being suitable for "prediction" and "realisation" purposes. This section compares the "prediction purpose" model to some existing evacuation models that have simulated the same fire scenarios in order to highlight the differences between the models. The comparison comprises two main evaluations. Firstly, the number of evacuees calculated in the model was compared to an existing model of the Rhode Island nightclub fire. Secondly, the numbers of deaths in the Rhode Island nightclub and the Gothenburg dance hall scenarios were compared to existing evacuation models that simulated deaths in the buildings.

The Rhode Island nightclub fire reports contain a section on computer simulations of nightclub evacuation scenarios (Grosshandler *et al*., 2005), and they simulated the number of evacuees who evacuated through each exit and the total evacuation time. One of their scenarios, which they considered to produce the closest results to the events that occurred in the actual fire disaster, was selected to be compared with the current model. Their scenario was designed as a trapped scenario by closing exits at different times, including the kitchen exit at five seconds, the platform exit at 30 seconds and the main door at 90 seconds. In addition, 420 people were placed throughout the nightclub and the model assumed that occupants would get trapped in the corridor when the main door blocked at 90 seconds. The results of their scenario show that 91 occupants evacuated through the front door, three people passed through the kitchen door, 32 people left through the platform door and the remainder (273 people) escaped through the main bar door. In addition to the occupants who escaped safely, 21 occupants were trapped in the entryway. In the actual fire disaster, 90 people evacuated through the front door, 46 people through the main bar side door, 12 people via the kitchen door, 20 people evacuated from the platform door and 79 occupants escaped through the windows.

The scenario for the "prediction purpose" model was developed by randomly placing 458 pedestrian agents throughout the building. The best results were calculated by the A* algorithm in the 0.5 m^2 grid-based Rhode Island nightclub scenario: 108 pedestrian agents left through the front entrance, 5 agents vacated through the main bar side exit, 79 agents escaped through the kitchen exit, 16 agents used the platform exit and 69 pedestrian agents evacuated through the windows. The rest of the pedestrian agents died or were rescued by the fire fighters. The number of evacuees in the "prediction purpose" model, Grosshandler *et al*.'s model, and the statistics for the actual fire disasters are displayed in Table 10-5, showing that the total percentage of similarities in the "prediction purpose" model was about 1.6 times better than Grosshandler *et al*.'s model. In summary, the model developed by this thesis includes an additional egress route, namely windows, and its results show greater similarity with the actual number of evacuees in real life.

Table 10-5 The results from Grosshandler *et al*.'s model and the model developed by this thesis

Egress Route	Actual Number of Evacuees at Each Exit	Grosshandler *et al*.'s Model (similarity to actual number)	Model* (similarity to actual number)
Front Entrance	90	91 (98.9%)	108 (80.0%)
Main Bar Side Exit	46	273 (0%)	5 (10.9%)
Kitchen Exit	12	3 (25.0%)	79 (0%)
Platform Exit	20	32 (40.0%)	16 (80.0%)
Windows	79	N/A (0%)	69 (87.3%)
Total Percentages of Similarities		**163.9%**	**258.2%**

*Data can be found in Figure 9-19, scenario 1

In addition to the number of evacuees, the model of this thesis also simulated deaths at the scene, whereas some of the evacuation models simulated that all the occupants safely evacuated the Rhode Island nightclub and calculated the total evacuation time (Grosshandler *et al.,* 2005; Chaturvedi *et al.*, 2006). One of the evacuation models simulated deaths in the Rhode Island nightclub fire, predicting 84 fatalities which was close to the actual number of deaths (89) in the fire disaster (Galea *et al*., 2008), whereas the "prediction purpose" model predicted a result that was slightly less accurate (82 deaths). Nevertheless, the model of this thesis has the advantage of simulating the distribution of deaths and thus can identify risk areas, which could not be defined in Galea *et al.*'s model. Another evacuation model simulated 96 casualties in the Gothenburg dance hall fire (Jiang *et al*., 2003), representing 47.6% similarity when compared with the actual number of deaths (63) in the disaster. The "prediction purpose" model simulated that 45 pedestrian agents died in the building, which improved the accuracy of the number of deaths to 71.4% similarity. In addition to the number of deaths, the model of this thesis also simulated the number of injuries, which was identified at a similarity level of 85.0%.

Overall, the model of this thesis, that was developed based on the study of human behaviour by the analysis of fire investigation reports, has improved egress selection by adding windows, has simulated better results of deaths, and output a wider range of results, such as the number of injuries and the distribution of deaths.

10.6 Chapter Summary

This chapter used Wilcoxon signed ranks test analysis to identify whether the results calculated by the two navigation algorithms were significantly different from each other. In addition, an overall view of the evacuation model was examined by the statistical analysis of results and observations of the simulation. Following that, common patterns across the different scenarios, the influences caused by the assumptions, and the potential issues caused by the situations that were excluded from the model were discussed. After reviewing the model, the model was validated and identified as suitable for the purposes of "prediction" and "realisation". To highlight the simulation results, the model was compared to three existing evacuation models and it is concluded that the model produced better results for egress selection, the number of deaths and injuries and the distribution of deaths. The final chapter provides a research summary and presents a conclusion of the research, including the contributions made by this thesis and potential end-users of the model. Finally, the potential directions for further research are suggested.

11. Conclusion and Further Work

Introduction and Background	Contents of Evacuation Modelling	Developing Research Questions	Developing an Evacuation Model	Simulation Outcomes	Discussion	Conclusion and Further Work
Ch. 1	Ch. 2	Ch. 3	Ch. 4, 5 and 6	Ch. 7, 8 and 9	Ch. 10	Ch. 11

11.1 Research Summary and Conclusion

This thesis aims to develop an agent-based evacuation model to ensure human safety in fire disasters. Issues identified following a review of previous research were summarised into four classifications: modelling human evacuation behaviour, modelling pedestrian movement in grid-based models, high-density simulation, and modelling human response in high-rise buildings (Section 3.2). Two main issues, modelling human behaviour and modelling pedestrian movement in grid-based models, were selected to be addressed in the evacuation model of this thesis (Section 3.4). Following that, the two main research questions were identified as follows:

1) Can an evacuation model be developed based on the study of fire investigation reports?

- What information can be extracted from fire investigation reports to be built into evacuation models?
- What kind of evacuation behaviour can be identified from fire investigation reports?
- How can evacuation behaviour be encompassed in evacuation models?

A new method of studying human behaviour by analysing fire investigation reports is proposed in this thesis as traditional methods such as video recordings and questionnaires have proven to be inefficient with regard to human behavioural analysis (Section 2.2.3). Therefore, the methodology for studying human behaviour from fire reports was introduced in Chapter 4. Firstly, Section 4.2 introduced the purposes of fire investigation, the content of official fire reports, the collection of resources and information related to human behaviour. Secondly, human behaviour and evacuation phenomena were identified using thematic analysis (Section 4.3). Based on these evacuation behaviours and phenomena, behavioural rules were defined for evacuation models (Section 4.4). Next, the characteristics and interactions between three agents (pedestrian, door and fire/smoke) were designed for the agent-based model (Chapter 5).

After the model was developed, the preliminary model was evaluated (Section 7.2) and modified (Section 7.3) in order to recreate accurate common human behaviours and evacuation phenomena. The final model produced simulation results in the 0.5 m^2 grid-based scenarios (Section 8.2) and the 0.3 m^2 grid-based scenarios (Section 9.2) via five tests. The five tests were designed to validate the evacuation model, using the egress selection to examine the realism of the model, the evacuation time, the number of deaths and the distribution of deaths to analyse the accuracy of the model, and the system run time that was scrutinised to determine the processing speed of the model.

According to comparisons of the simulation results and the fire statistics, the model successfully recreated the situations of egress selection and the number of deaths and injuries when using the A* algorithm in the 0.5 m^2 grid-based scenarios (Section 10.4). In addition, the distribution of deaths was moderately representative of the actual fire disaster, particularly the Rhode Island nightclub scenario. As a result, this thesis concludes that the model successfully simulated human behaviour in terms of the study of fire investigation reports.

2) Which combination of navigation algorithm and pedestrian size simulates results that are closest to real life situations?

- Which algorithms should be developed in the evacuation model?
- What issues do the current navigation algorithms encompass?
- How can the limitations of current navigation algorithms be improved?
- What size of pedestrian should be developed in the evacuation model?

It was decided the model should simulate pedestrian movement using the grid-based approach in order to simplify calculation and allow geo-location (Section 3.2.5). The size of the grid (0.5 m^2 and 0.3 m^2) was developed in terms of average human body size (Section 6.2). In addition, the A* algorithm and the Priority Queue Flood Fill algorithm were selected to calculate pedestrian egress route in the model (Section 2.6.4). However, the issue of fixed route selection occurred in the standard calculation, so this thesis presented a novel navigation algorithm, adding calculating steps and available directions of movement to the standard calculation, and pedestrian agents were programmed to select routes based on the calculation of steps and directions rather than the value calculated on each grid (Section 6.3).

All the scenarios in the model used four combinations of parameters (two navigation algorithms and two grid sizes) to simulate pedestrian evacuation movement. The results of tests that were calculated using the A* and the Priority Queue Flood Fill algorithms in the 0.5 m^2 grid-based scenarios were displayed in Section 8.2, and the differences between the 0.5 m^2 and the 0.3 m^2 grid-based scenarios were compared in Section 9.2. After the validation of the model, the comparisons showed that the combination of the A* algorithm and the 0.5 m^2 grid-based scenarios performed the best simulation outcomes, which produced results with high realism and accuracy (Section 10.4).

11.2 Contributions

This thesis makes contributions to the development of evacuation modelling in the following ways:

1) Studies human behaviour in an efficient way by analysing fire investigation reports

Fire reports are one of the resources produced following fire disasters. These investigation reports are written by experts after every fire disaster, so do not involve trying to collect primary fire video data from a damaged building, the difficult of analysing video recordings of a smoke-filled scene, or time spent reviewing questionnaires. A range of information is covered in the reports including a description of the building and its construction, observations, statements made by witnesses or suspects, fire scene diagrams and photographs, analysis, findings and recommendations offered by the fire investigation team.

Not only can human behaviour be analysed from studying the content of fire reports, a variety of information about the layout of the building and circumstances surrounding the specific fire disaster can also be studied for a better development of the scenario in the model. In addition, more evidence is provided from different points of view by the people who played different roles in relation to the fire incidents. Overall, this method reduces time spent analysing video recordings of a specific fire case and increases the accuracy of human behaviour observed during a wide range of fire disasters. In conclusion, this is a novel use of data, as no research has been conducted using this way of studying human behaviour before.

2) Additional evacuation behaviour - approaching windows

Occupants sometimes escape through windows as they try to flee fire, and this behaviour is mentioned in many fire reports. Therefore, the model designed windows to be available for egress selection for pedestrian agents during evacuation. When comparing the number of people who escaped through windows in the actual Rhode Island nightclub fire, where windows were the second most popular egress route, the simulation results were identified as showing high percentage of similarity. Therefore, windows are considered to be important egress routes for occupants inside a building. Indeed, if the model simulates a large number of people evacuating through windows, the number and usability of exits and windows should be examined in the actual building. However, despite their importance, windows have not been included in previous fire modelling research.

3) Estimates the number of injuries

The model not only simulates the number of deaths, but also the number of injuries, which are not simulated in many evacuation models. The injuries featured in the model include pedestrian agents who were rescued by the fire fighters after they fainted on the floor and those who jumped or evacuated through the windows. According to comparisons of the simulation results and the fire statistics, the number of injuries was identified as one of the high percentages of similarities. Therefore, the model successfully estimates the number of injuries, and thus is useful for prevention because those who suffer injuries have a high possibility of dying at the scene.

4) Identifies risk level by area

The model also classifies the space into potential risk areas and calculates the number of deaths in each region, which has not previously been simulated in existing evacuation models. Although the results in the model were not significantly representative of the events occurring in the actual fires, this identification method has great potential to be developed in further research. If the model can accurately predict where people might die in the building, it can suggest priority rescue plans to fire fighters for a faster rescue or help the owners to make improvements to avoid many deaths occurring in one place.

5) Improvement of navigation algorithms

The model solves the limitations of the current calculation, which the standard A* algorithm and the Priority Queue Flood Fill algorithm calculate a fixed route from a starting point to the final destination. In this model, pedestrian potential movements between two points increased to multiple route selections by comprising additional calculation steps and available directions of movement when calculating the cost on each grid.

6) Validating the evacuation model by the combinations of different navigation algorithms and pedestrian body sizes

This thesis validates the simulation outcomes that were calculated by different combinations of navigation algorithms (the A* algorithm and the Priority Queue Flood Fill algorithm) and pedestrian sizes (0.3 m^2 and 0.5 m^2). Five tests were designed to validate the realism, accuracy and performance speed of the evacuation model, and each of the combinations was determined to one of the purposes (realisation or prediction) that is suitable for the model after the comparisons. This validation method has not been used in the previous similar research, so these comparisons provide an overall view of the influences of different navigation algorithms and pedestrian body sizes.

11.3 Potential End-Users

After the validation, the 0.5 m^2 grid-based evacuation model using A* algorithm was identified suitable for realisation and prediction purposes, and the 0.5 m^2 grid-based evacuation model using Priority Queue Flood Fill algorithm was used for prediction purpose (Section 10.4). According to the definition in Section 1.2, the realisation type of models, which simulates existing or past scenarios in order to understand the issues in the environment, can be used for current usage and post-disaster research; the prediction type, which simulates influences that might change the design of buildings or future events, can be used for design and planning. A number of purposes and usages for realisation and prediction types of evacuation models are displayed in Table 11-1.

Table 11-1 The purposes and usage of realisation and prediction types of evacuation models

Realisation	Prediction
● Ensure safety of existing buildings ● Manage pedestrian flow ● Identify what happened in a fire disaster ● Identify potential risk areas in a building ● Identify how occupants evacuate during a fire ● Suggest priority order for rescue areas	● Predict safety of building design ● Predict pedestrian flow at an event ● Predict what might happen after changing current layout ● Predict potential risk areas in a building ● Predict where people might gather during a fire and improve the area

Based on the purposes and usages identified above, the following summarises potential end-users of this model.

1) Design and planning

Running evacuation simulations for future constructions or proposed events can help to predict the impact of the design or configuration and ensure the safety of people. A suitable and safe configuration could be established, with estimated pedestrian flow, designed evacuation plans, and safety issues identified, according to the simulation results. This type of model is suitable for planners, designers, and developers when construction is at the initial design and planning phase and thus can easily be changed if issues are found at this early stage.

2) Current usage

The evacuation model can be used to educate and train people to become familiar with an environment or deal with hazards. In addition, participants could suggest efficient escape routes or improve congestion areas after understanding any possible risks. Therefore, this type of model is suitable for helping instructors, managers and operators to understand their current environment and address any safety issues.

3) Post disaster research

The evacuation model could recreate past disasters to establish the reasons for serious damage or loss of life. This tool could help researchers, investigators and police to understand what happened in the fire event and why the disaster was so serious. The information could subsequently be used to apply findings to other locations in order to avoid similar disasters in the future.

11.4 Further Work

The evacuation model was developed based on a limited number of human behaviours and evacuation phenomena, and a number of issues were not addressed in the model due to the complexities of model development and the limitations of time, knowledge and equipment. Therefore, this section summarises some potential solutions and interesting directions for further work.

1) Evacuation timeline

The model developed an evacuation timeline for the stages of "evacuation" and "perish", excluding the "pre-movement" stage, which is considered the longest period during the evacuation. This stage influences individual overall evacuation time that is related to human safety. Therefore, further research could focus on the issues of pre-evacuation movement, the identification of pre-movement time and the implementation of the evacuation model for the more accurate prediction of evacuation time.

In addition, the model assumes the fire alarm starts when the fire spreads, and all the pedestrian agents start evacuating at the same time. However, there is sometimes a time lag between the start of the fire and the point at which the fire alarm detects the smoke, and this gap might significantly influence the evacuation process. Therefore, it is important to study the connections between times at different stages of both human behaviours and the fire itself.

2) Human behaviour

A number of human behaviours were identified from the fire reports, but the limited number of human behaviours developed in the model might have caused some of the low percentages of similarities between the results and the fire statistics. For example, a different distribution of deaths occurring in reality might be influenced by occupants who helped each other and thus died as a group at a specific location. Therefore, group behaviour should be studied in the further development of the model.

Furthermore, human evacuation behaviour in different countries might vary. Different examples of evacuation movement in fire disasters might have been affected by cultural characteristics, weather conditions and building codes. As a result, studying human behaviour in different countries could be an interesting issue for future development of the model.

Fire reports might also have provided a limited number of human behaviours, so further psychological, physiology and social studies are required in order to reach a better understanding of individuals and human interactions.

3) Fire and smoke conditions

A different field of research in to the form of fire and smoke conditions was not studied in this thesis. Although the type of fire and smoke can be identified according to the flame, its density and its smell, every fire disaster is unique due to the fact that fire can be influenced by various conditions in an environment such as heat, materials, temperature and humidity. In addition to these factors, the objects in the building can influence the spread of fire and smoke when the fire burns furniture or decorations. Therefore, further studies on the causes of different kinds of smoke and spread of fire could improve the fire/smoke simulation in the model.

4) Model development

A number of human behaviours and evacuation phenomena were developed for generic agent-based models in this thesis. In addition, the model uses the A* and Priority Queue Flood Fill algorithms to calculate pedestrian movement on the two grid sizes (0.5 m^2 and 0.3 m^2). However, the behaviour can be implemented in different modelling approaches using different navigation algorithms in different pedestrian sizes of grid-based or continuous model. For example, human behaviour can be implemented in social force models using the continuous approach to test which of the approaches simulate better results.

In the model, assumptions were created to simulate specific situations, generalise human behaviour or reduce the complexity of modelling process. These assumptions might influence evacuation time, evacuation movement and other impacts as displayed in Table 10-2. In order to develop an efficient and accurate evacuation model, further research could modify these parameters and improve the simulations in the model.

5) Related applications

The model simulates pedestrian evacuation movement in fire disasters. In order to represent a group of objects moving in an environment, the model can be modified to simulate different situations or fields of crowd movement by changing the characteristics and the interactions of agents. For example, stampedes, traffic congestions, animal migrations and riot attacks. Firstly, the model could simulate a group of people stepping on bodies while they are pushing and falling down on top of each other. Secondly, the application for traffic changes a group of people into vehicles, simulating the driving behaviour and the movement of vehicles on the road. Next, a group of animals usually follows common patterns when they are gathering together, and one of the implementations could be animal migration in different seasons.

Finally, the model could simulate the interaction of crowds, rioters and police during a protest.

11.5 Final Research Overview

Evacuation modelling has been an active research area for many years, involving the simulation of a group of people evacuating from a hazardous area. This study has used an efficient method to study human behaviour and has developed a pedestrian evacuation model that can be applied to real world application. Use of this tool can reduce the risks of practising evacuation drills and help people to understand the most efficient evacuation routes when a disaster happens. More attention should be focused on the realism and accuracy of evacuation modelling due to its important implications for protecting human lives and properties. In addition, simulations substitute humans, objects or phenomena in order to challenge a real system that is not accessible, or achieve dangerous or difficult tasks. It is hoped that such research will continue to be developed in the near future to help ensure human safety in any environment.

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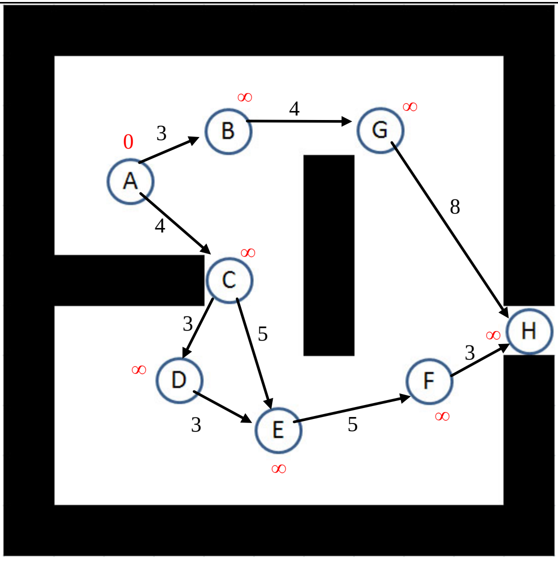
Appendix A Navigation Calculation

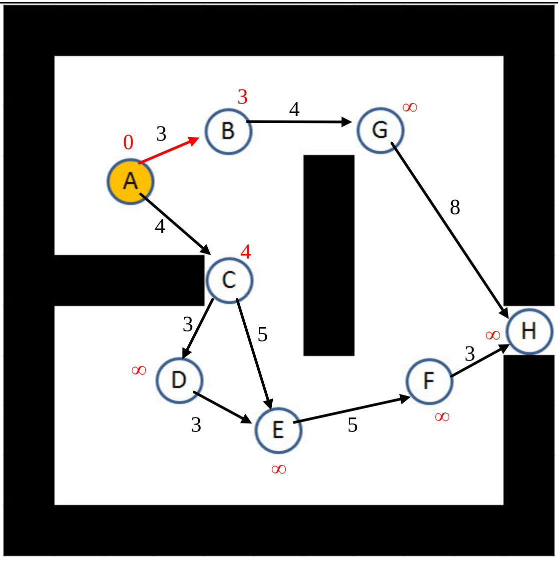
A.1 Dijkstra's Algorithm

An example of a room, which contains walls and a single exit, was designed to simulate how a pedestrian avoid obstacles (walls) whilst moving towards an exit. The calculation was based on a typical network road map using seven nodes to represent potential passing locations (Figure A-1), and the environment was divided into grids to show the calculation method for grid-based evacuation models (Figure A-2).

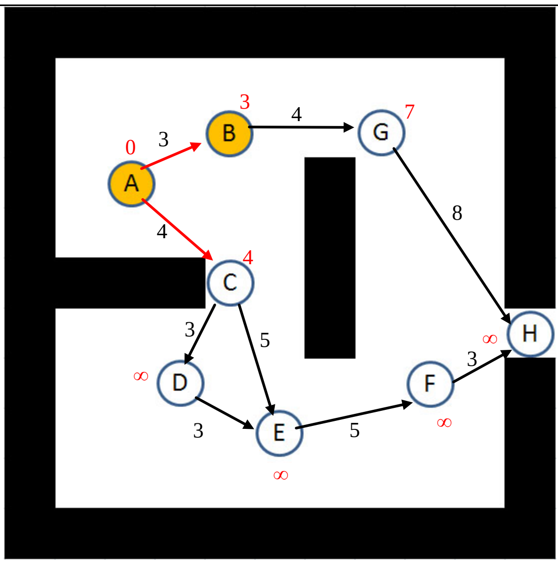
In Figure A-1, the calculation steps show a person who starts from position A move to exit H using Dijkstra's algorithm. Figure A-1a is the original road map, in which the black cells represent walls, the weighted distances and directions are pre-defined and unvisited nodes are assigned. The distances from current node A to its neighbours B and C are three and four respectively (Figure A-1b), so the lowest distance cost is node B, which becomes the next current node. With the addition of distance to node G (Figure A-1c), the distance cost (7) becomes greater than distance cost (4) on node C; therefore, the next current node C is selected for the next step (Figure A-1d). When the distance cost is calculated to be less than the value that was calculated in the previous steps, the node will update to a lower value (Figure A-1e). Figure A-1f and g show the addition and selection from step IV repetition until it determines the lowest distance cost (the shortest path) to the final destination (Figure A-1h).



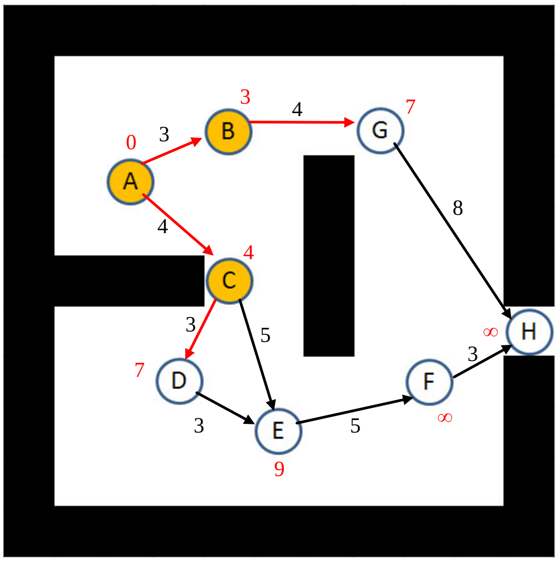
a. Assign distance values and unvisited nodes (white).



b. Identify the shortest distance (red arrow) from a visited node (yellow).

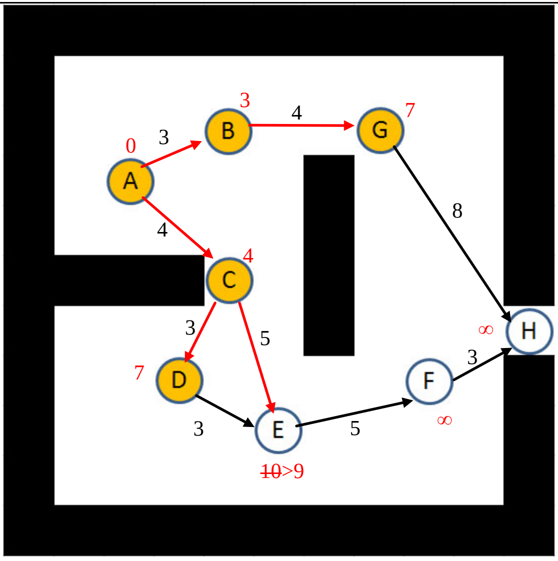


c. Calculate the distance cost from node B and select the lowest distance cost (node C) which is compared to the previous calculations.

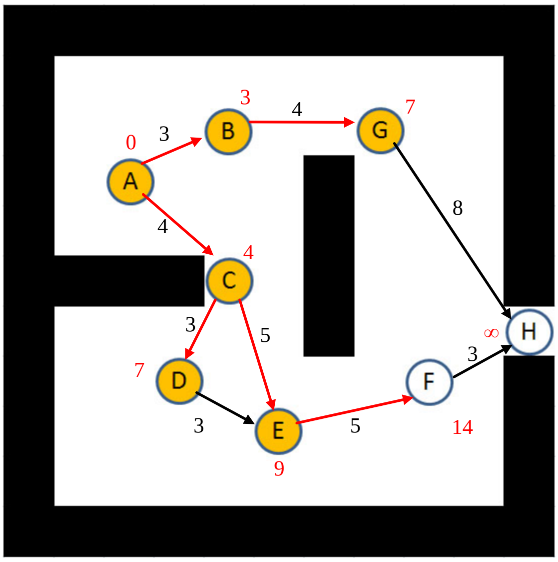


d. Both node D and G have the same distance cost, so they both become the next current nodes.

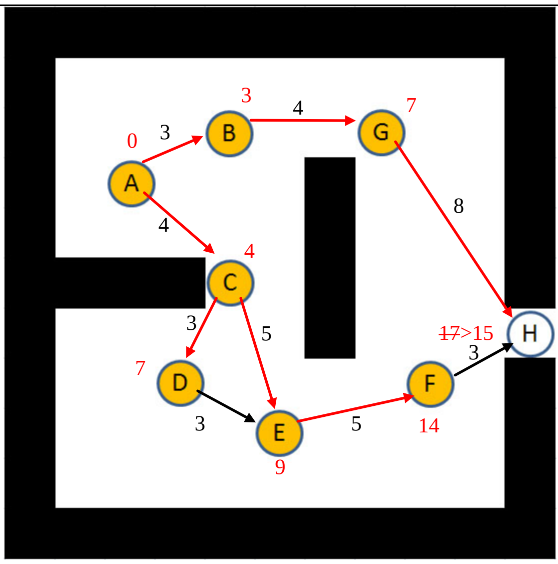
Figure A-1 The shortest path calculation from position A to exit H using Dijkstra's algorithm



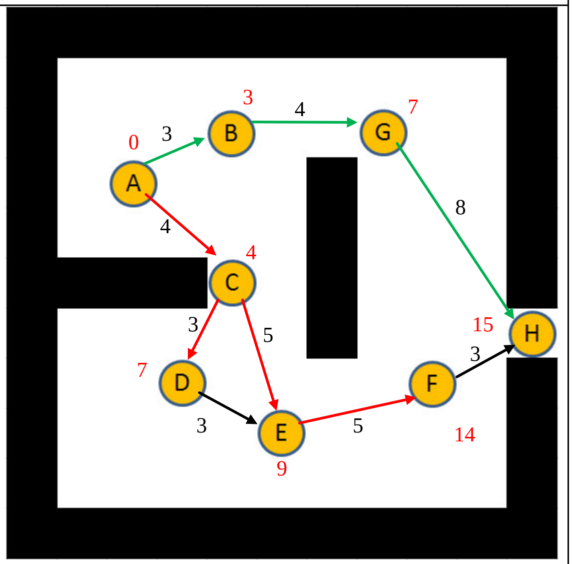
e. The distance cost from node D to E is greater than from node C to E, so it remains the lower distance cost.



f. Calculate the distance cost on node F.



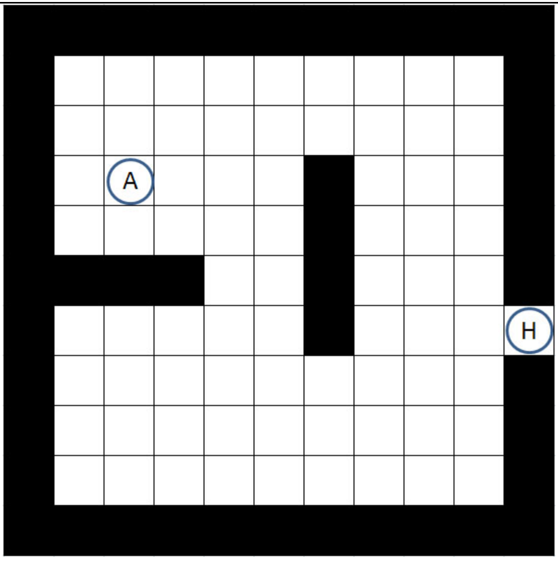
g. Compare the distance cost from node F to H (17) and node G to H (15).



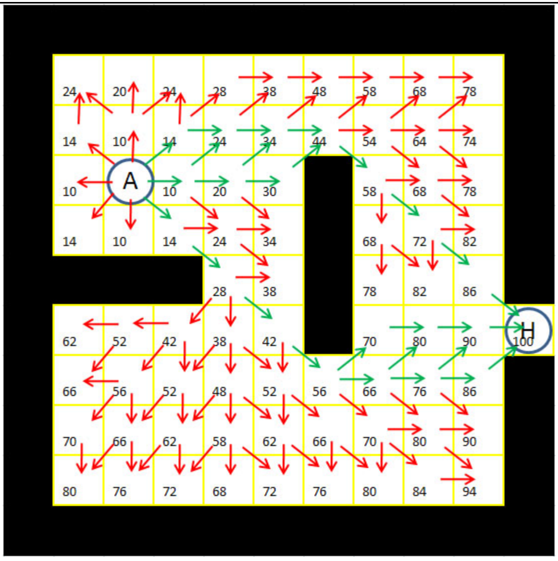
h. The final shortest path starts from node A, B, G, to H (green arrows).

Figure A-1 continued. The shortest path calculation from position A to exit H using Dijkstra's algorithm

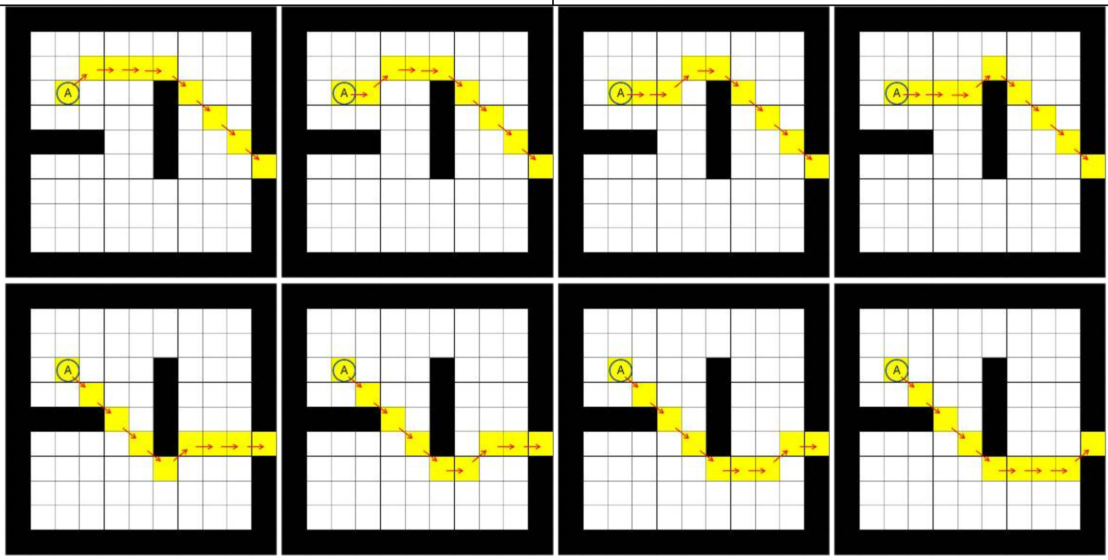
Figure A-2a is a grid transformation of the configuration from Figure A-1, where each cell represents a node and an edge is a distance between two cells. In grid-based models, each cell is connected to eight neighbours, and the distance of the horizontal/vertical direction is set as 10, whereas the diagonal distance is 14 (to simplify the calculation of $\sqrt{2}\times 10$). Figure A-2b shows the result of distance cost in each cell and potential movement directions after calculation. Finally, it identifies eight shortest paths with the same lowest distance cost (100) in this space (Figure A-2c).



a. Grid-based space that is generated from Figure A-1.



b. Each cell calculates a distance cost and potential movement directions.



c. Eight shortest routes with the same lowest distance costs.

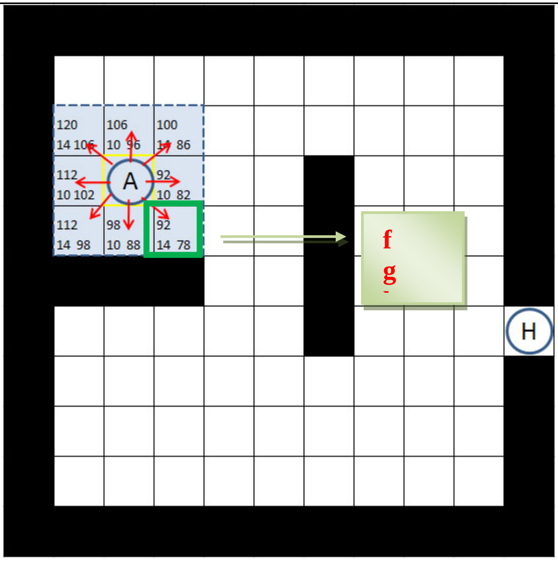
Figure A-2 Pedestrian movement using Dijkstra's algorithm on a grid-based graph

A.2 A* Algorithm

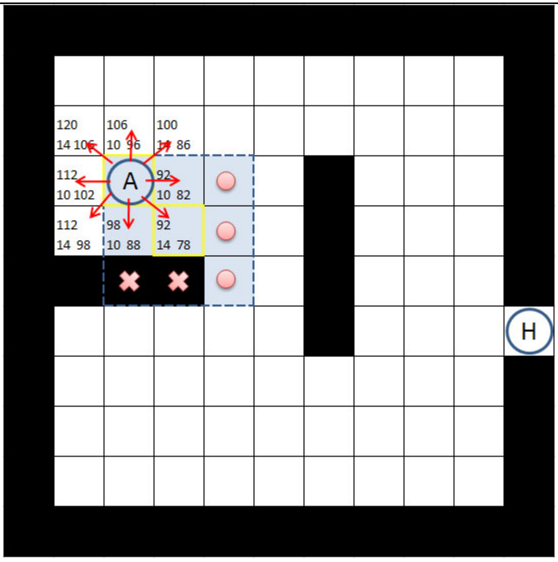
Figure A-3 explains the path finding calculation steps of the A* algorithm using a diagonal heuristic. In Figure A-3a, node A represents a starting point and node H represents the final target. The A* calculation begins from the starting point as it searches eight neighbours around the cell. In each cell, the value ‘g’ is set to determine the lowest distance from starting point A to each cell: every cell distance is set to 10 and the diagonal distance to 14 (to simplify the calculation of $\sqrt{2} \times 10$). Additionally, ‘h’ represents the distance from the final target to the calculating cell, and calculates the distance by ignoring obstacles such as walls. The total score is shown at the top of each grid cell as ‘f’.

After calculating eight neighbour cells, the algorithm sets the current cell as a visited cell and selects the lowest score from the pre-calculated values to continue to the next step. If there is more than one cell with the same lowest value, it will select the cell with a lower h score that is closer to the final destination. For example, the yellow frame is selected in Figure A-3b, because the h score (78) is smaller than another value (82) of the cells that have the same lowest distance-plus-cost score (92).

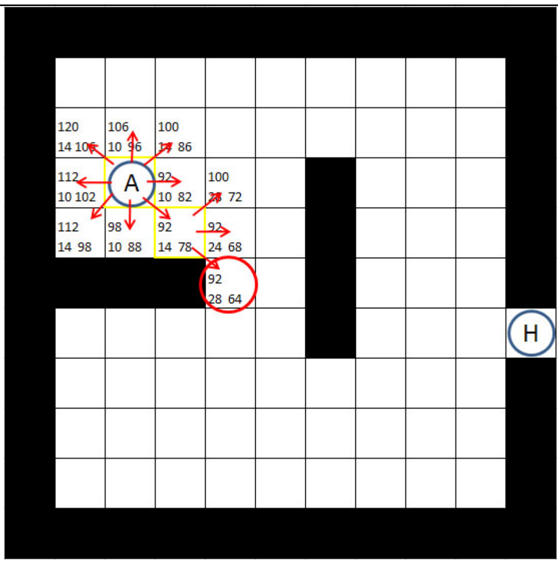
If the adjacent cells are obstructions, such as obstacles or walls, the cells are identified as close cells. Figure A-3c and d show the available directions for movement and selections of the A* algorithm according to the lowest distance-plus-cost score from the pre-calculated values. The value of the distance-plus-cost is updated with a lower value during the calculation (Figure A-3e and f) in order to ensure the pedestrians move in the correct direction towards the final target. Figure A-3g shows the final calculation and the result of the shortest path route.



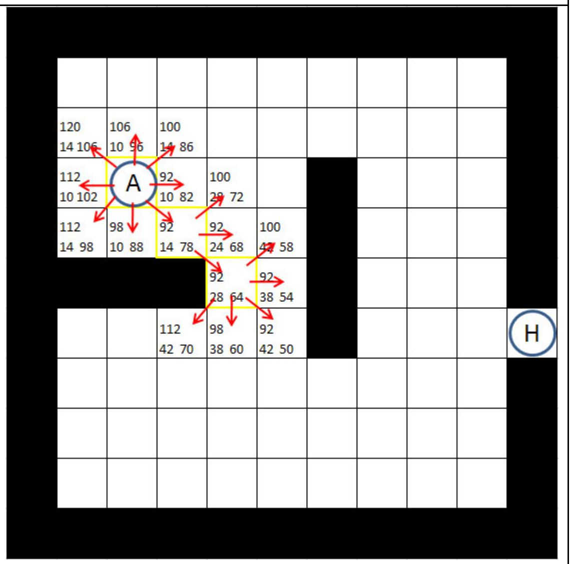
a. The value ‘g’ is the distance from the current node A to each cell, ‘h’ is the distance from each cell to the final exit, and ‘f’ is the distance-plus-cost score from the sum of both values.



b. Select the lowest distance-plus-cost value and continue to the next cell (cells in yellow frame represent visited cells). If more than one cell has the same 'f' values, it selects a cell with a lower 'h' score that is closer to the target.

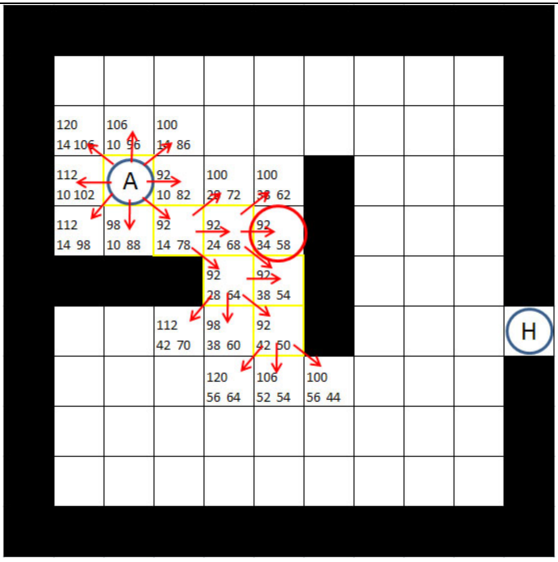


c. Red arrows represent the available movement directions from node A to the selected lowest cost cells.

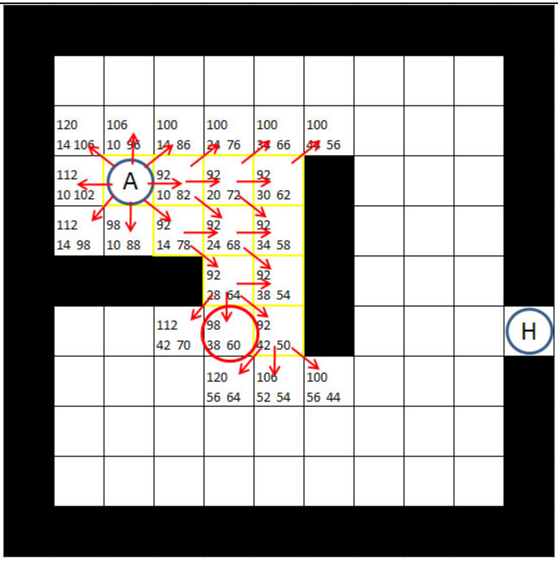


d. It searches the lowest distance-plus-cost from the pre-calculated values.

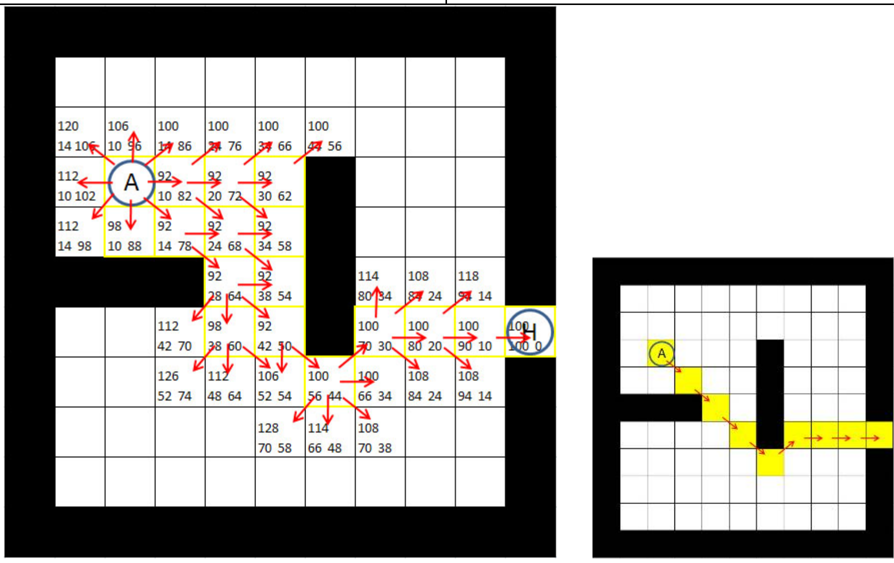
Figure A-3 The steps of the A* path finding calculation using a diagonal heuristic



e. The value of distance-plus-cost is updated if it calculates a lower score.



f. Updated lower values and select the next lowest distance-plus-cost value.



g. Final calculation and one shortest path.

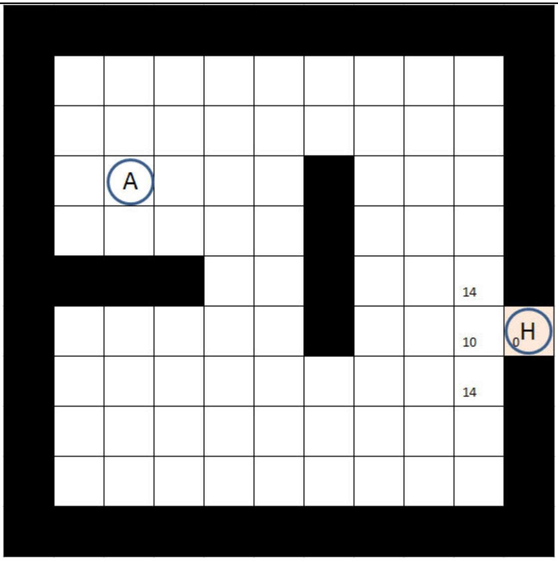
Figure A-3 continued. The steps of the A* path finding calculation using a diagonal heuristic

A.3 Recursive Flood Fill Algorithm

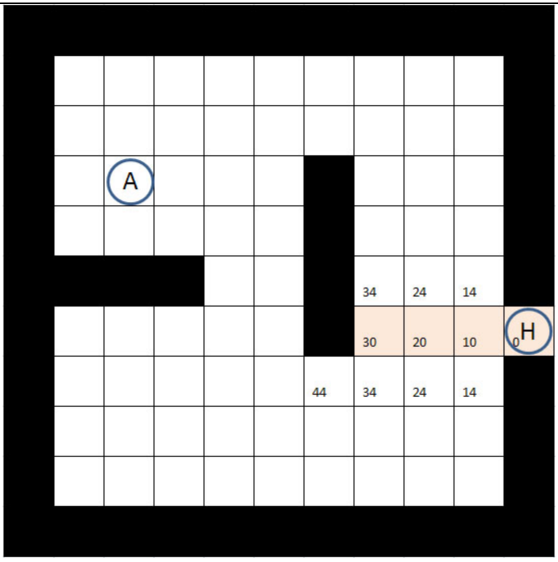
The Recursive Flood Fill algorithm starts from the final destination, calculating the distance of cells around the exit H (Figure A-4a). Next, it moves to the next cell and calculates the distance values of adjacent cells, whereas the direction of visiting cells follows a loop function as an example of west, north, east, south, north-west, north-east, south-east and south-west (Figure A-4b). If the current cell is located at the end of a visiting array, it will begin by visiting the next direction; for example, from west to north as displayed in Figure A-4c.

The calculation continues by following the priority of visiting directions, and a visited cell which calculates a lower distance cost than the previous value is updated and assigned to unvisited (Figure A-4d, e, and g). The algorithm continues visiting cells and calculating distance costs in order to ensure all cells are visited and every cell has a lowest distance cost (Figure A-4f). If there are no unvisited neighbours around the current cell, the algorithm returns to the nearest node (the priority in calculation array) that contains adjacent unvisited cells and starts visiting cells from another direction (Figure A-4h).

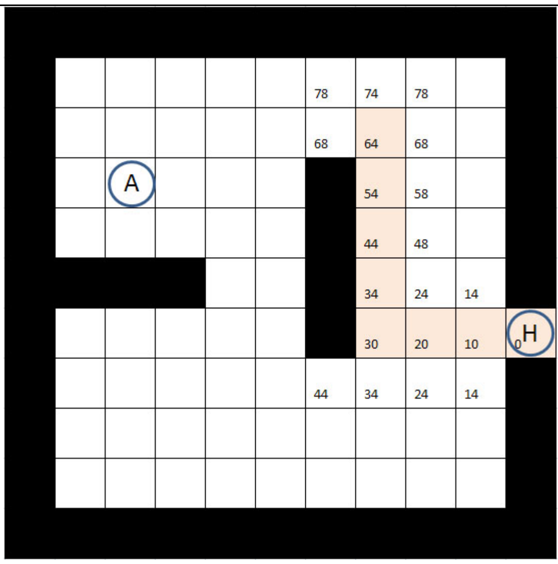
The Recursive Flood Fill algorithm repeats step III until all the cells are visited and every cell contains a lowest distance cost. Figure A-4i shows the directions of visiting cells and the lowest value of each cell, and the final potential table is displayed in Figure A-4j using colour to represent the distance from the exit. Finally, two potential paths are identified from starting node A to the final target (Figure A-4k).



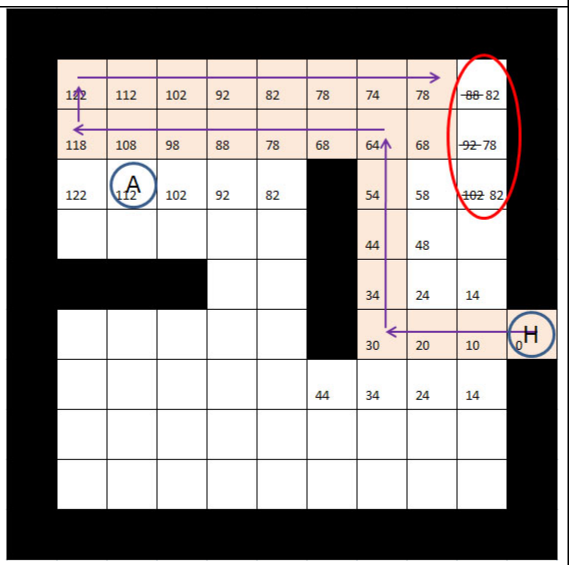
a. Calculate the distance values of adjacent cells around the exit (coloured cells represent visited cells).



b. Calculating the distance cost of each cell, which follows a priority of visiting directions; for example: west, north, east, south, north-west, north-east, south-east and south-west in this case.

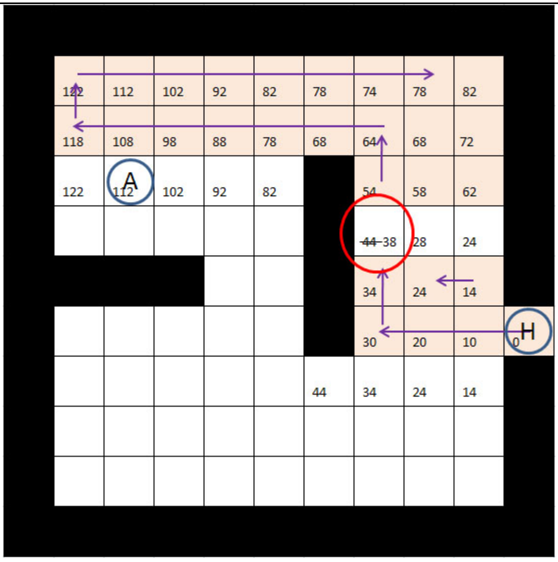


c. Change a visiting direction if the cell is located at the end of a visiting array.

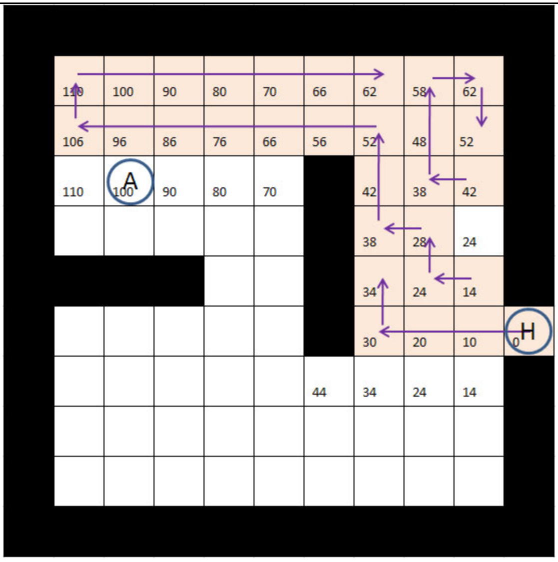


d. A cell is updated by a lower distance cost.

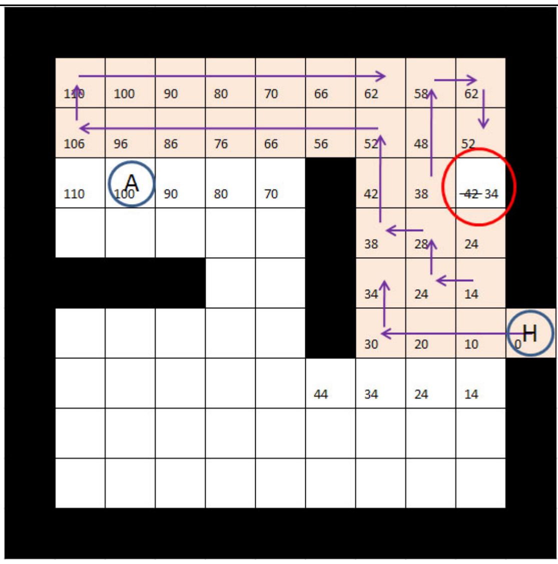
Figure A-4 A potential table that is calculated using the Recursive Flood Fill algorithm



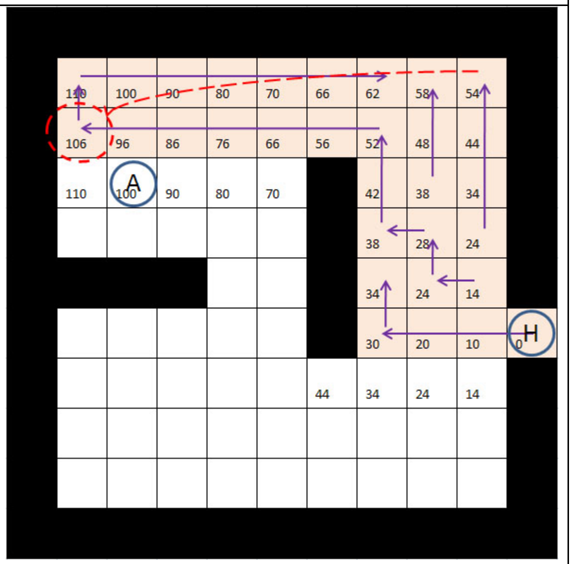
e. A visited cell is updated and assigned to unvisited.



f. The algorithm continues calculating to check if every cell has a lowest distance cost.

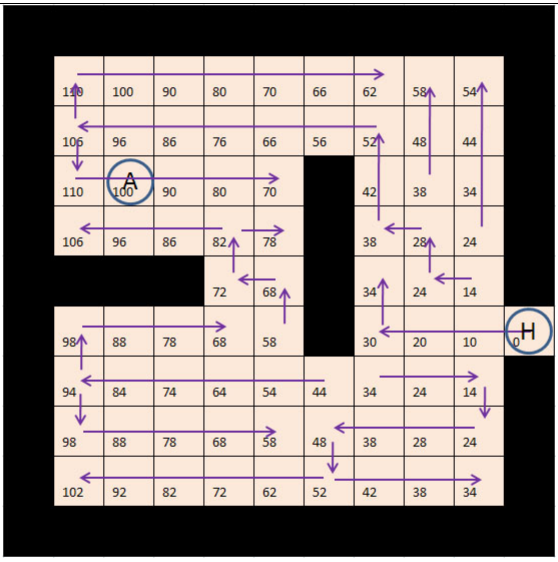


g. Cells are updated by lower distance values.

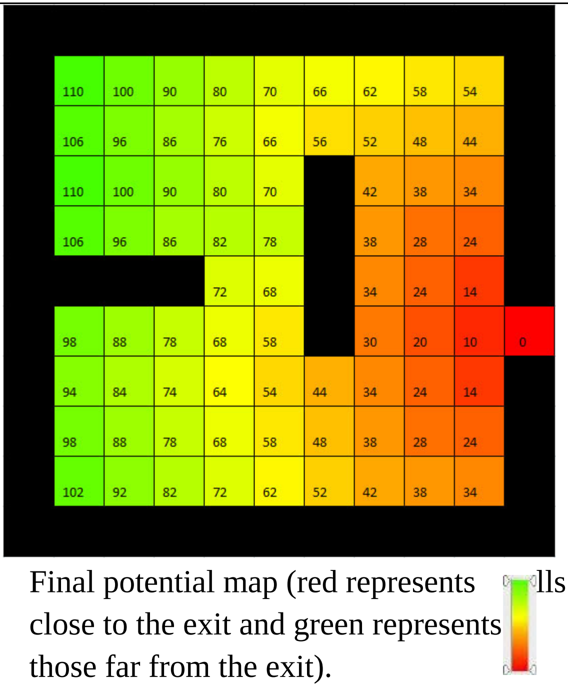


h. If the neighbour nodes of a current cell are all visited, it returns to the nearest node that contains adjacent unvisited cells.

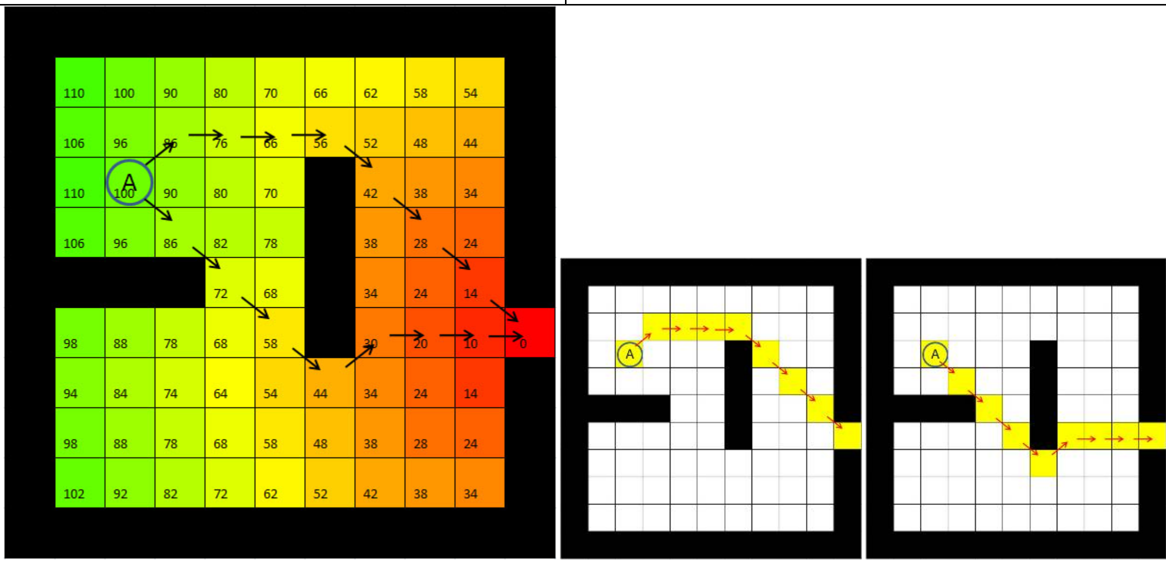
Figure A-4 continued. A potential table that is calculated using the Recursive Flood Fill algorithm



i. All cells are updated by the lowest distance cost.



j. Final potential map (red represents cells close to the exit and green represents those far from the exit).

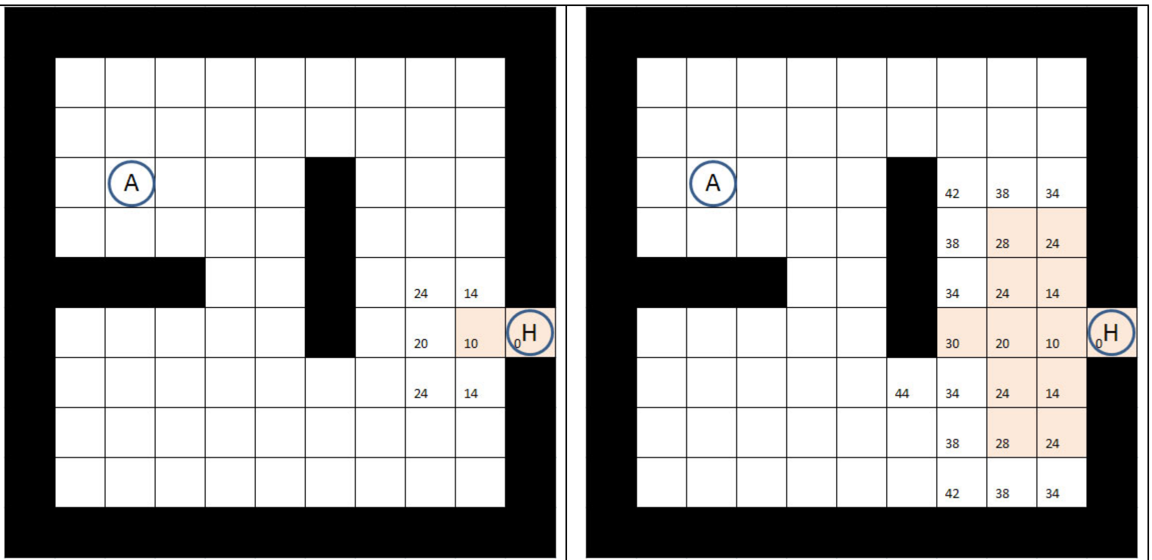


k. Potential table with moving directions and two potential paths.

Figure A-4 continued. A potential table that is calculated using the Recursive Flood Fill algorithm

A.4 Priority Queue Flood Fill Algorithm

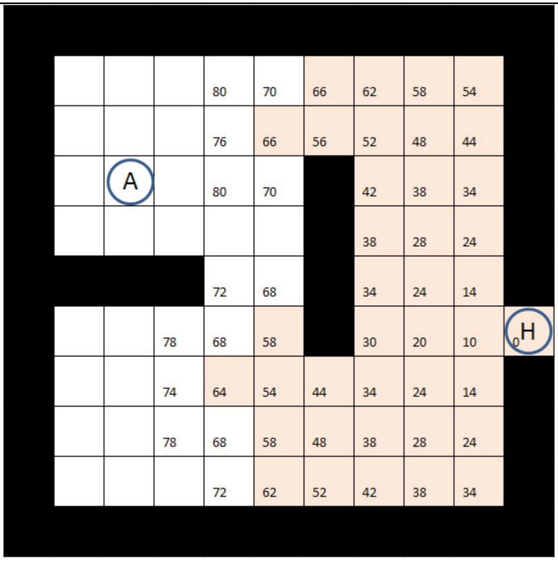
Figure A-5 shows the calculation for producing a potential table using the Priority Queue Flood Fill algorithm. The algorithm starts from the final destination and selects the lowest distance cost as the next visited node (Figure A-5a). Next, it assigns a cell with the lowest distance cost to a priority queue node instead of visiting cells from a specific direction (Figure A-5b). The calculation continues with step II (put the cell with the lowest distance cost in the queue and calculate its neighbour nodes) until all cells are visited and every cell contains the lowest distance value (Figure A-5c). Finally, the potential map is created (Figure A-5d), and the result shows two potential paths from starting node A to the exit (Figure A-5e).



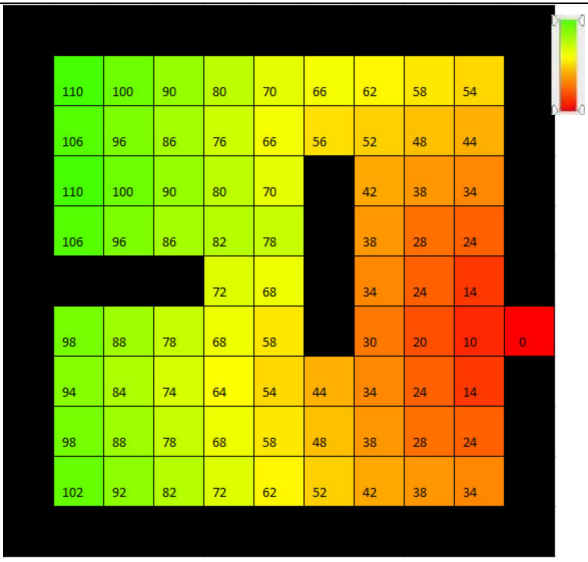
a. Calculate the distance of adjacent cells and select the lowest distance cost to be the next current node (the coloured cells represent visited cells).

b. Assign the same lowest distance costs in the priority queue and calculate their adjacent cells.

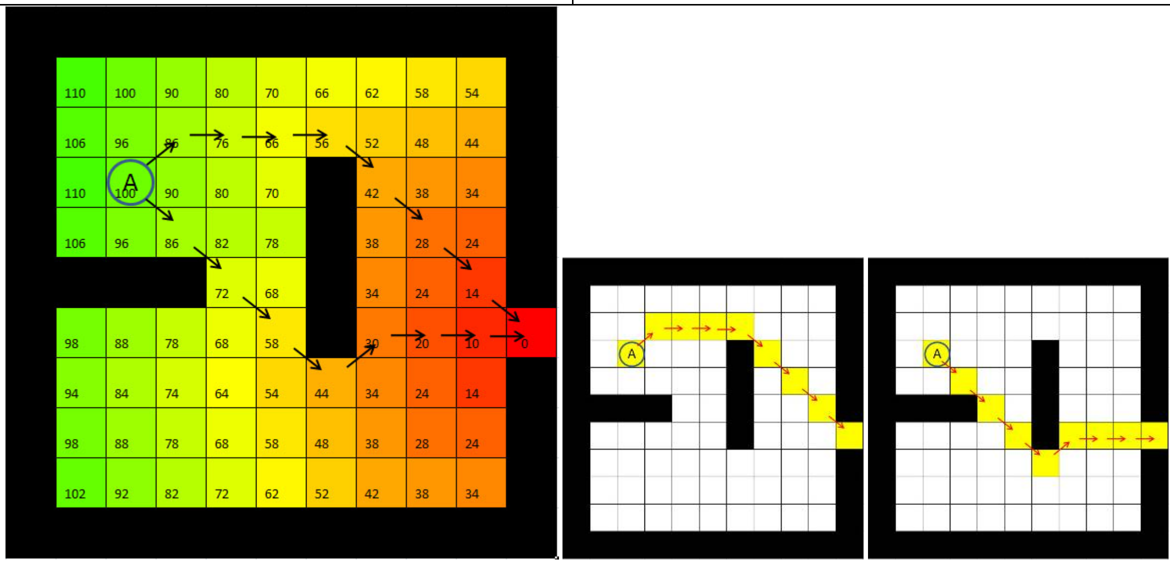
Figure A-5 A potential table that is calculated using the Priority Queue Flood Fill algorithm



c. Continue the calculation as the same loop: put the lowest distance cost in the queue and calculate its neighbours.



d. Final potential map (red represents cells close to the exit and green represents those far from the exit).



e. Potential table with moving directions and two potential paths.

Figure A-5 continued. A potential table that is calculated using the Priority Queue Flood Fill algorithm

Appendix B Summary of Fire Reports

Table B-1 "Investigation Report on the MGM Grand Hotel Fire, Las Vegas, Nevada" by Best and Demers (1982)

Date	21, November, 1980
Fire time	07:16 to unknown
Type of building	Hotel, Commercial Building
Building size	23 storeys (380 feet by 1200 feet)
Mean of egress	6 stairways on the guest floors
Fire starting point	Deli (hotel restaurant)
Total number of occupants	3400
Casualties	85 died, 600 injured
Location and number of deaths	High-rise tower: 61 (rooms: 25, corridors: 22, stairways: 9, elevator: 5) Casino level: 18 Jumped from windows: 1 Others: 5
Human behaviour	• People were alert to the fire when they heard or saw fire apparatus, saw or smelled smoke, or heard people yelling or knocking on doors. • People took refuge in rooms. • People broke windows to signal rescuers or to get fresh air. • Staff tried to fight the fire, but was told not to put water on an electrical fire. • Staff used extinguisher to fight the fire.
Issues	• Rapid fire and smoke development due to available fuels. • Lack of fire extinguishment. • Unprotected vertical openings contributed to smoke spread. • Substandard enclosure of interior stairs, smoke proof towers and exit passage ways.

Table B-2 "Beverly Hills Supper Club Fire, Southgate, Kentucky" by Best and Swartz (1978)

Date	28, May, 1977
Fire time	20:45 to unknown
Type of building	Nightclub, Commercial Building
Building size	2 storeys (240 feet by 260 feet)
Mean of egress	8 exits
Fire starting point	Zebra Room - a meeting room on second floor
Total number of occupants	2400-2800, with approximately 1200-1300 people attending a show in the Cabaret Room (the main showroom).
Casualties	164 died, 70 injured
Location and number of deaths	Main showroom exit A: 125 Main showroom exit B: 34 Other: 3, Hospital: 2
Witness statement	Employee statements: • People smelled smoke and investigated its source. • People closed the door when seeing the smoke, told other employees, and started to use fire extinguisher fight the fire. • Some people started moving after employee told people to leave, others just sat there. • People thought the notice was the comedy show effect (a joke), but some people started moving. Nobody was panicking at the beginning. • One door was locked. • Before people saw the smoke, they were orderly and no any chaos, screaming, or panicking. • We couldn’t help those people without legs (disabilities) Parton statements: • Some people went out through the main entrance and others through the kitchen. • The comedians were saying the show will continue when the fire is out as they were trying to let people calm. • The smoke came down quickly • When the smoke coming, people started pushing and shoving. The panic started when people saw the smoke • It took 30 seconds for the smoke to reach the exits. • People changed direction and went back because of the crowd. • The smoke was heavy, thick, and black • The door going outside was fairly wide, but it was

	a single exit. • People were falling out of the door. • People stood on the table to find another path, but later he jumped back into the crowd again because it didn’t lead outside.
Human behaviour	• People investigated the smoke source. • People fought the fire • Staff acted differently to guests (guest were passive) • Before panic, people moved orderly. • After panic, people started pushing when they saw the smoke. • People changed their route when they saw the crowd. • People searched alternative way.
Issues	• Overcrowded. • No sprinkler or standpipe systems. • No alarm system. • No fire or smoke detection systems.

Table B-3 "College Dormitory Fire, Dover, Delaware" by Carpenter (1987)

Date	12, April, 1987
Fire time	02:33 to unknown
Type of building	Dormitory, Residential Building
Building size	3 storeys
Mean of egress	Unknown
Fire starting point	Room 206 on second floor
Total number of occupants	Unknown while the fire happened (the building is designed for 180 students)
Casualties	1 died, 4 injured
Location and number of deaths	Room 220: 1
Human behaviour	• People ignored smoke, because they thought it was a smoke bomb. • A person stated he tried to evacuate but became confused. He, therefore, returned to his room and closed the door, and hid under a desk. • People were rescued from the 3rd floor window.
Issues	• People ignored smoke. • Fire alarm did not work (the bell was stolen). • Lack of smoke detectors. • No sprinkler systems or smoke detectors.

Table B-4 "Sixteen-Fatality Fire in Highrise Residence for the Elderly, Johnson City, Tennessee" by Carpenter (1989)

Date	24, December, 1989
Fire time	17:00 to unknown
Type of building	Nursery House, Residential Building
Building size	11 storeys
Mean of egress	N/A
Fire starting point	1st floor, living room
Total number of occupants	145
Casualties	16 died, 35 injured
Location and number of deaths	6th floor elevator lobby: 1 Room 107: 1 Higher floors: 14
Human behaviour	• People ignored fire alarm. • People hesitated to venture out into sub-freezing temperature. • People returned to their apartments to await rescuers instead of finding alternative routes.
Issues	• No sprinkler system. • Only one smoke detector. • Limitation of elderly. • Smoke travelled at ceiling level.

Table B-5 "Indianapolis Athletic Club, Indianapolis, Indiana" by Chubb (1992)

Date	5, February, 1992
Fire time	23:45 to 02:38
Type of building	Hotel, Commercial Building
Building size	9 storeys (100 feet by 200 feet)
Mean of egress	One service stairway provided direct, unobstructed access to all floors, three stairways served 3-6 floors, and five stairways served above the 6th floor, confusing occupants who needed to change stairways at 3rd and 6th floor.
Fire starting point	3rd floor
Total number of occupants	45-50
Casualties	1 died, 8 injured
Location and number of deaths	Stairway (6th to 7th floor): 1
Human behaviour	• People trapped at upper floor because of the fire at the lower level, and these people were rescued by using aerial ladders. • People used an elevator to evacuate. • Staff searched the fire location. • People were aware of fire because of hearing the fire alarm and the fire department’s arrival. • People went back to collect belongings. • People dressed and collected things before evacuating.
Issues	• Concealed spaces. • Unenclosed stairways. • Confusing exit arrangement. • Mechanical system control. • Fire detection and suppression systems. • Delayed evacuation. • People returned to the building.

Table B-6 "Dance Hall Fire, Gothenburg, Sweden" by Comeau and Duval (2000)

Date	28, October, 1998
Fire time	23:42 to 02:02
Type of building	Nightclub, Commercial Building
Building size	2 storeys (35.4 m by 9.5 m)
Mean of egress	2 exits to stairways and windows
Fire starting point	Stairway of the south east building
Total number of occupants	400 (permitted volume was 150 people)
Casualties	63 died, 180 injured
Location and number of deaths	Main entrance: 43 Refuge room: 20
Witness statement	• It was very crowded inside of the dance hall. • So many people that it was impossible to dance. • People became aware of fire when lights around the stage started to pop. • Others who were further away from the stage reported observing smoke, but at first they thought it was from cigarette smoke.
Human behaviour	• Congestion caused by the number of people attempting to flee the fire through this single door. • Others broke out the windows and jumped to the ground. • People were being pushed out of the windows by those behind them. • Bodies lying on the stairs. • A wall of bodies inside of the doorway that reached the top of the doorjamb.
Issues	• Overcrowded. • Lack of fire alarm systems. • Ignition of combustible fuel load in a stairway. • Only one door to evacuate because another door was blocked by fire. • Windows were too high to reach (2.2 m from floor).

Table B-7 "Seven Fatality Fire at Remote Wilderness Lodge, Grand Marais, Minnesota" by David (1991)

Date	12, July, 1991
Fire time	04:21 to unknown
Type of building	Lodge, Residential Building
Building size	3 storeys (60 feet by 60 feet)
Mean of egress	2 stairways
Fire starting point	1st floor, dining room area
Total number of occupants	14
Casualties	7 died, 6 injured
Location and number of deaths	1st floor: 1 2nd floor: 4 3rd floor: 2
Human behaviour	• People escaped from large casement style windows (they survived). • People jumped from windows. • One victim was restricted by a wheelchair (this person died).
Issues	• Open stairways. • Evacuation plans and procedures should be practiced.

Table B-8 "Investigation into the King's Cross Underground Fire, London, United Kingdom" by Fennell (1988)

Date	18, November, 1987
Fire time	19:25 to unknown
Type of building	Underground, Transit Station
Building size	N/A
Mean of egress	N/A
Fire starting point	Escalator
Total number of occupants	N/A
Casualties	31 died
Location and number of deaths	N/A
Witness statement	• I didn't think it was very serious, so I didn't leave the booking office. • Black smoke with a rubbery or plastic smell. • The smoke became thick and black and made breathing difficult and visibility poor. • It was impossible to see or breathe as the heat became intense. • Feel hazy and hot, noted it was fairly smoke, but people were no panic and soon heard people shouting "get out". • About "flashover", people heard a "whoosh" and flames shot across from the top of the escalators. • People escaped back down the escalators and were evacuated by train.
Human behaviour	• People were screaming. • People evacuated by train. • People believed the fire was small, so they didn't leave. • People took refuge. • People were no panic at the beginning of the fire.
Issues	• People tended to light up while going up the escalator to leave the station. • Lack of smoke detectors. • Staff needed to be trained in evacuation, communication, fire-fighting and incident control procedure.

Table B-9 "Report of the Technical Investigation of the Station Nightclub Fire, West Warwick, Rhode Island" by Grosshandler *et al*. (2005)

Date	27, February, 2003
Fire time	23:08 to 01:07
Type of building	Nightclub, Commercial Building
Building size	1 storey (4484 feet^2)
Mean of egress	Three available exits, whereas one exit was not considered accessible to the patrons
Fire starting point	Upper wall, left of platform stage
Total number of occupants	458
Casualties	96 died, 230 injured
Location and number of deaths	Front entrance: 31 Rooms: 7 Storage area: 10 Dart room: 9 Sunroom: 27 Other: 12
Witness statement	• I could feel myself walking over people. • People fell to the floor, and others were piling up on top. • Nobody wanted to give up their spot, because people felt like it would just be put out. • We both turned and headed for the main door, which was the only door we knew about. • We could see people coming out of the windows. • The light went off.
Human behaviour	• People did not immediately move upon first noticing the flames. • People only knew the main front door. • People exited the building through its windows. • People were unfamiliar with the building. • Between 56-66% of the occupants tried to evacuate through the single main entrance. • People jammed in doorway at 01:42 after the fire started.
Issues	• The rate of egress from the main entrance was limited by the single doorway inside the vestibule. • Kitchen exit was unavailable to patrons. • Difficulties to open the main bar exit.

Table B-10 "Five-Fatality Highrise Office Building Fire, Atlanta, Georgia" by Jennings (1989)

Date	30, June, 1989
Fire time	10:29 to after 20:00
Type of building	Office, Commercial Building
Building size	10 storeys (200 feet by 200 feet)
Mean of egress	2 stairways in each tower (North and South Towers)
Fire starting point	6th floor of the south tower
Total number of occupants	>40 on the 6th floor
Casualties	5 died, 23 injured
Location and number of deaths	Refuge room: 1 (without breaking windows) Escaping way: 3 Other: 1
Human behaviour	• People jumped from 6th floor (the fire floor). • People broke windows and waited for rescue. • People died in the corridor or in the office where the windows were not broken. • People sought refuge • Group sought refuge and broke windows to let fresh air came in. After that, one of them jumped and others were rescued via a ladder or rescued by fire fighters. • People trapped in the office.
Issues	• No automatic sprinklers. • No smoke detectors on the 6th floor. • Fire alarm system problem. • Evacuate under fire conditions took longer time than evacuation drills (this case: 7.5 minutes > 6 minutes). • Hazardous area should be separated.

Table B-11 "Nine Elderly Fire Victims in Residential Hotel, Miami Beach, Florida" by Jennings (1990)

Date	06, April, 1990
Fire time	03:00 to 07:30
Type of building	Hotel, Commercial Building
Building size	3 storeys with 102 guest rooms (200 feet by 90 feet)
Mean of egress	N/A
Fire starting point	1st floor, the ceiling space of the storage room
Total number of occupants	140
Casualties	9 died, 20 injured
Location and number of deaths	Evacuating: 7 Elevator: 1 Room: 1 (due to dress and collect valuables)
Human behaviour	• People smelled smoke – investigate the source. • People knocked on doors to awaken guests. • Most of people were asleep. • People got dressed and collected valuables before leaving (this person died). • People took an elevator (this person died).
Issues	• No sprinkler system. • Evacuation drills should be encouraged.

Table B-12 "Kona Village Apartments Fire, Bremerton, Washington" by Kimball (1997)

Date	13, November, 1997
Fire time	06:00 to unknown
Type of building	Apartment, Residential Building
Building size	2 storeys at north tower and 4 storeys at east, south, and west towers (270 feet by 320 feet)
Mean of egress	6 foot walkways
Fire starting point	Apartment 316 on 3rd floor
Total number of occupants	50
Casualties	4 died, 11 injured
Location and number of deaths	Rooms on the 4th floor: 4 (all >75 years old)
Human behaviour	• People were rousing other residents by knocking on doors. • People escaped by helping each other through the smoke. • People were exiting in their walkers, crutches, and wheelchairs. • Staff searched fire origin (a smoke detector sounding on the 3rd floor). • People still asleep. • At least 21 occupants were rescued via exterior ladders on the outside wall. • All people escaped with only the clothes on their backs, which no one picked up belongings. • People appeared at many windows.
Issues	• Lack of sprinklers. • Wooden stairwells and walkways. • Lack of adequate fire fighters access to apartment entrances. • Lack of interconnected smoke detectors and exterior alarms. • Insufficient number and spacing of hydrants. • Accessibility of hydrants. • Lack of sufficient operating space for fire vehicles.

Table B-13 "Apartment Building Fire, East 50th Street, New York City" by Kirby (1988)

Date	11, January, 1988
Fire time	20:19 to 22:16
Type of building	Apartment, Residential Building
Building size	10 storeys, 120 units (100 feet by 70 feet)
Mean of egress	2 stairwells and exterior fire escapes
Fire starting point	First floor
Total number of occupants	> 56
Casualties	4 died, 2 injured
Location and number of deaths	Stairwell (1st – 2nd floor): 1 9th floor apartment with a door opened: 1 10th floor stairwell (near the door to the roof): 2
Human behaviour	• People made aware of fire by other residents and by smoke penetrating their units. • People escaped from exterior fire escapes. • People were rescued from windows. • People who stayed in their apartments behind closed doors were unharmed.
Issues	• People left door to be opened, letting the smoke escape. • People did not immediately report the fire. • People used elevator during the fire.

Table B-14 “Five Fatality Residential Motel Fire, Thornton, Colorada” by Miller (1997)

Date	27, January, 1997
Fire time	02:30 to 03:58
Type of building	Hotel, Commercial Building
Building size	3 storeys
Mean of egress	2 open stairways
Fire starting point	The bottom of a stairway
Total number of occupants	162
Casualties	5 died
Location and number of deaths	Own rooms (2 units): 4 Corridor: 1
Human behaviour	• People took refuge in the room.
Issues	• “Centre loaded” corridors. • Rooms without windows. • Lack of automatic sprinklers. • Lack of building-wide fire detection and alarm systems. • Combustible concealed space. • Unprotected vertical opening (the fire started at the lowest level with smoke, heat, and fire spreading up the open stairway into enclosed corridor).

Table B-15 "Twelve-Fatality Hotel Arson, Reno, Nevada" by Ockershausen and Cohen (2008)

Date	31, October, 2006
Fire time	22:00 to unknown
Type of building	Hotel
Building size	4 storeys (122 feet by 136 feet)
Mean of egress	4 exterior fire escapes and 3 interior staircases
Fire starting point	2nd floor
Total number of occupants	82
Casualties	12 died, 31 injured
Location and number of deaths	Corridor: 7 Rooms: 4 Other: 1
Witness statement	• People saw light smoke, but when walking toward to the stair, the smoke became very heavy and dark. • The smoke was so thick that he couldn’t see and fell down the steps. • People heard the fire alarm but still remained in his room until the smoke coming under the door. • People were forced to exit through the rear of the building because of the intense heat and smoke.
Human behaviour	• People ignored the fire alarm. • People were trying to jump from windows. • People left when the smoke came into the door.
Issues	• No automatic sprinkler systems. • Some people ignored the fire alarm.

Table B-16 "Interstate Bank Building, Los Angeles, California" by Routley (1988)

Date	04, May, 1988
Fire time	22:37 to 02:19
Type of building	Office, Commercial Building
Building size	62 storeys (124 feet by 184 feet)
Mean of egress	4 main stairways
Fire starting point	12th floor (an open-plan office area)
Total number of occupants	50
Casualties	1 died, 37 injured
Location and number of deaths	12th floor: 1
Human behaviour	• Staff investigated the source of the alarm. • Staff reset the fire alarm for 4 times. • People evacuated to the rooftop and were rescued by helicopters. • People evacuated via elevators. • People crawled to an exit stairway. • People evacuated via stairs.
Issues	• Falling glass from upper floors. • Sprinkler systems were not completed. • Building personnel shut off the alarm. • The building should have protected elevators for fire service. • Smoke in stairways. • Fire protection systems needed to be tested regularly.

Table B-17 "Apartment Complex Fire, 66 Units Destroyed, Seattle, Washington" by Schaeman (1991)

Date	21, September, 1991
Fire time	21:20 to 03:51
Type of building	Apartment, Residential Building
Building size	4 storeys (200 feet by 234 feet)
Mean of egress	3 potential ways to escape from each unit (96 units) • Through their front door down the short hallway, then along the exterior walkways in either direction to a staircase. • Through a bedroom window directly to the walkway. • From their rear balcony or rear window.
Fire starting point	First floor
Total number of occupants	260
Casualties	0 died, 8 injured
Location and number of deaths	None
Human behaviour	• People jumped, dropped or climbed down from windows and balconies. • People did not believe fire alarm. • People helped their own family and neighbours. • People fought the fire. • People took care of their children. • People searched alternative routes. • People left until they threatened by smoke or flames.
Issues	• People ignored the fire alarm. • Low-income apartment: people used candles when their power was cut off. • No sprinkler systems.

Table B-18 "Doubletree Hotel Fire, New Orleans, Louisiana" by Shapiro (1987)

Date	19, July, 1987
Fire time	22:00 to 03:17
Type of building	Hotel, Commercial Building
Building size	17 storeys (18,000 square feet)
Mean of egress	3 stairwells on each floor
Fire starting point	Outside Room 1001 on 10th floor
Total number of occupants	>150
Casualties	1 died, 10 injured
Location and number of deaths	10th floor corridor: 1
Human behaviour	• Staff searched origin location. • Staff fought the fire. • “Convergence Cluster”: group took refuge to wait for rescue. • People reported the lobby they found/smelled smoke. • Staff took the elevator without any protect. • People tried to open the window (but failed). • People ignored the fire alarm due to previous false alarms.
Issues	• Automatic alarm failed. • Lack of sprinkler system. • Staff action was not correct.

Table B-19 "Success Story at Retirement Home Fire, Sterling, Virginia" by Stambaugh (1989)

Date	16, December, 1989
Fire time	16:29 to 19:37
Type of building	Apartment, Residential Building
Building size	3 storeys (104 units)
Mean of egress	N/A
Fire starting point	3rd floor, mechanical room
Total number of occupants	73
Casualties	0 died, 0 injured
Location and number of deaths	None
Human behaviour	• Security guard called 911. • Residents had frequent fire drills, so they were no panic during evacuation. • People thought it was another fire drill practice, but it shouldn't so close to the time of the wedding, so they decided to evacuate.
Issues	None

Table B-20 "Chicken Processing Plant Fires, Hamlet, North Carolina" by Yates (1991)

Date	3, September, 1991
Fire time	08:15 to 12:00
Type of building	Industrial Building
Building size	1 storey (30,000 square feet)
Mean of egress	7 exits (3 locked)
Fire starting point	Processing room
Total number of occupants	90
Casualties	25 died, 54 injured
Location and number of deaths	Cooler: 12 Space adjacent to fire origin: 7 Other: 6
Human behaviour	• People sought refuge after finding the door locked. • People searched alternative routes. • People kicked locked exit.
Issues	• Several exits locked. • No evacuation plan. • Open space without door to close.

Appendix C Agent-Based Modelling Toolkit: Repast

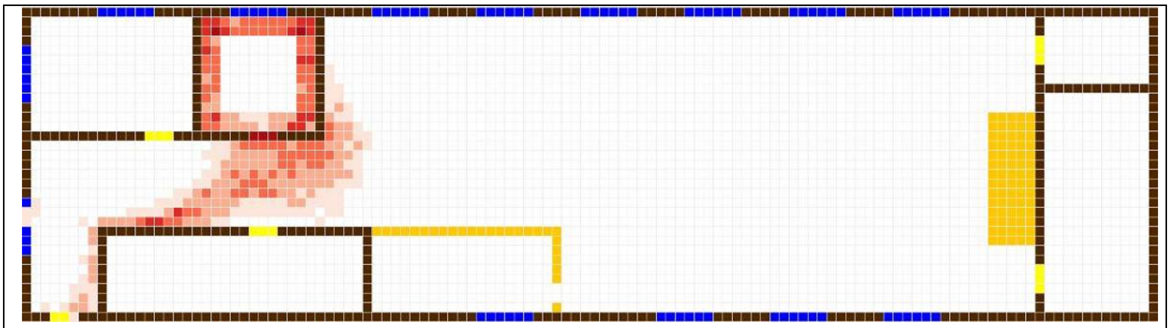
Repast (Recursive Porous Agent Simulation Toolkit) is a free, open source, and cross-platform agent-based modelling and simulation toolkit, which was originally developed by the University of Chicago, and further support the continual development by Argonne National Laboratories (North *et al*., 2006). One of the latest version, Repast Simphony, is a Java based modelling system which was extended by the Repast. Its model development uses a mixture of Java, Groovy, and flow charts to complete genetic algorithms, system dynamics, and social network modelling (Repast, 2012), so it can be easy used by both beginners and experienced programmers. It also includes some key features as follows:

- Visual model development.
- A point-and-click model platform and operation.
- Flexible nested definition of space, including networks, 2D, 3D, and GIS formats.
- Connected model text file and database storage.
- Batch run read variables in parameter files for multiple runs without user-interaction.
- Built-in adaptation libraries for genetic algorithms, neural networks, regression, random number generation, and specialised mathematics.
- Built-in logging and graphing tools.
- Automated connections to external programs for statistical analysis and visualisation of model results.

In addition, the team of Repast creates an online support mailing list, the Repast Interest mailing list (http://lists.sourceforge.net/lists/listinfo/repast-interest), to obtain technical questions and help solving problems between a large variety of users. The advantage of this mailing list is that users can learn from the discussion of these technical questions. Therefore, Repast Simphony was considered the most suitable agent-based modelling toolkit of this research, using Java programming to develop multi-agent behaviour, complex interactions, and navigation algorithms.

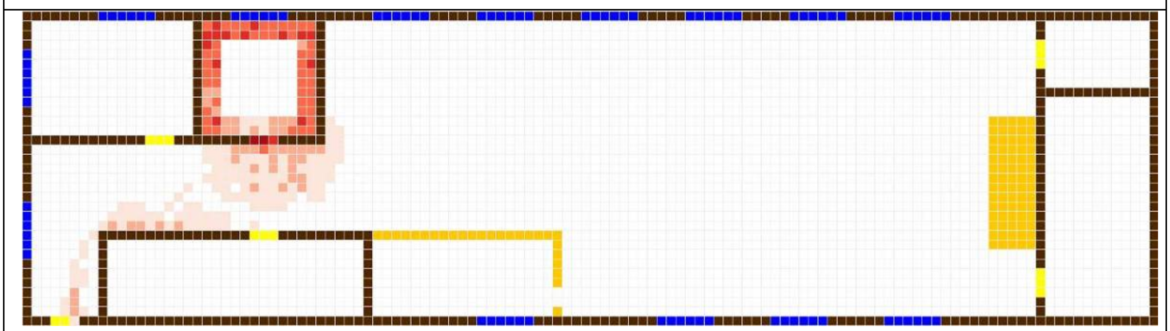
Appendix D Distribution of Deaths in the 0.3 m^2 Grid-Based Scenarios

Case 1: Gothenburg Dance Hall



Wall Window Exit/Door Obstacle No Risk (0-5.5%) Risk Lv. 1 (5.5-17.4%)
Risk Lv. 2 (17.4-30.3%) Risk Lv. 3 (30.3-43.1%) Risk Lv. 4 (43.1-63.3%) Risk Lv. 5 (63.3-100%)

(a) A* algorithm

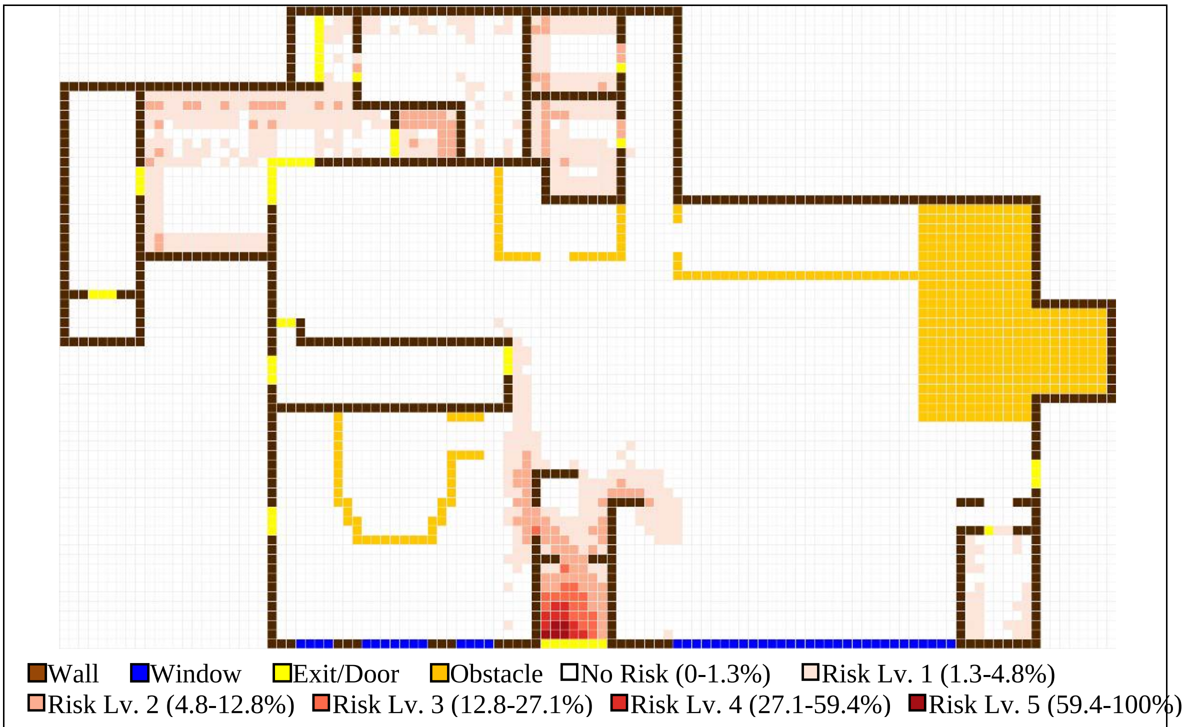


Wall Window Exit/Door Obstacle No Risk (0-4.3%) Risk Lv. 1 (4.3-13.7%)
Risk Lv. 2 (13.7-26.1%) Risk Lv. 3 (26.1-39.8%) Risk Lv. 4 (39.8-59.6%) Risk Lv. 5 (59.6-100%)

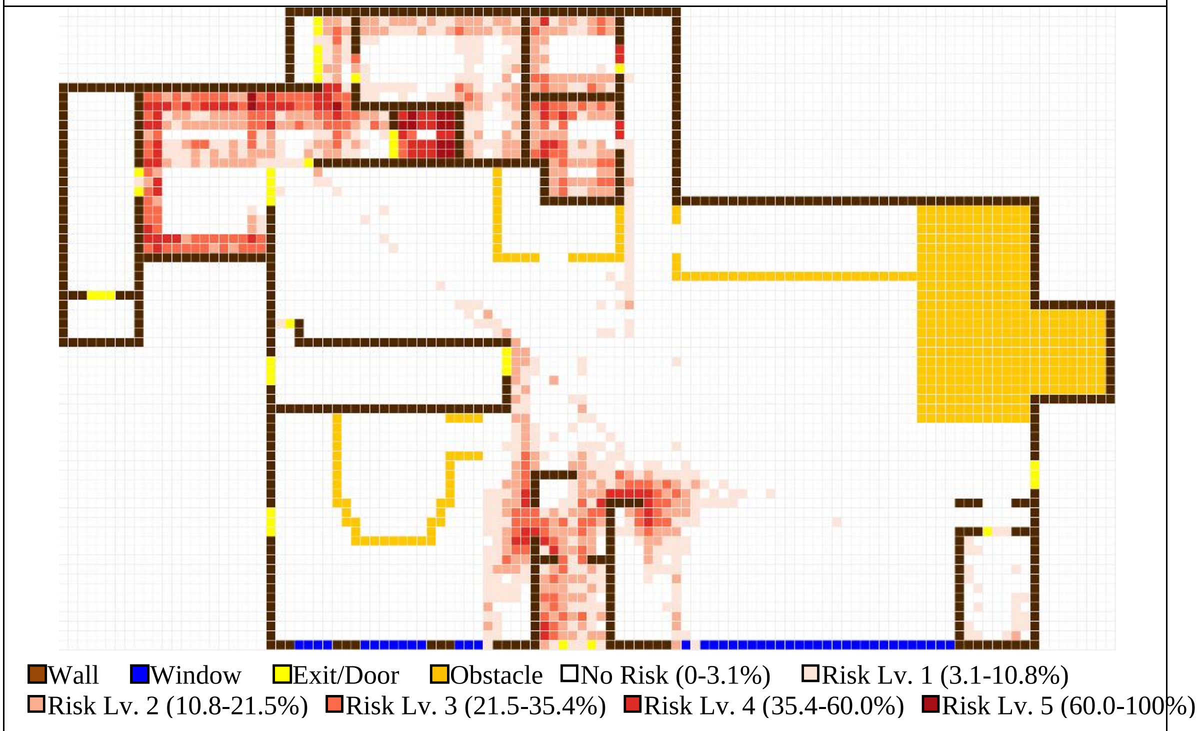
(b) Priority Queue Flood Fill algorithm

Figure D-1 The potential death locations in the 0.3 m^2 grid-based Gothenburg dance hall scenario.

Case 2: Rhode Island Nightclub



(a) A* algorithm



(b) Priority Queue Flood Fill algorithm

Figure D-2 The potential death locations in the 0.3 m^2 grid-based Rhode Island nightclub scenario.

Case 3: Hamlet Chicken Processing Plant

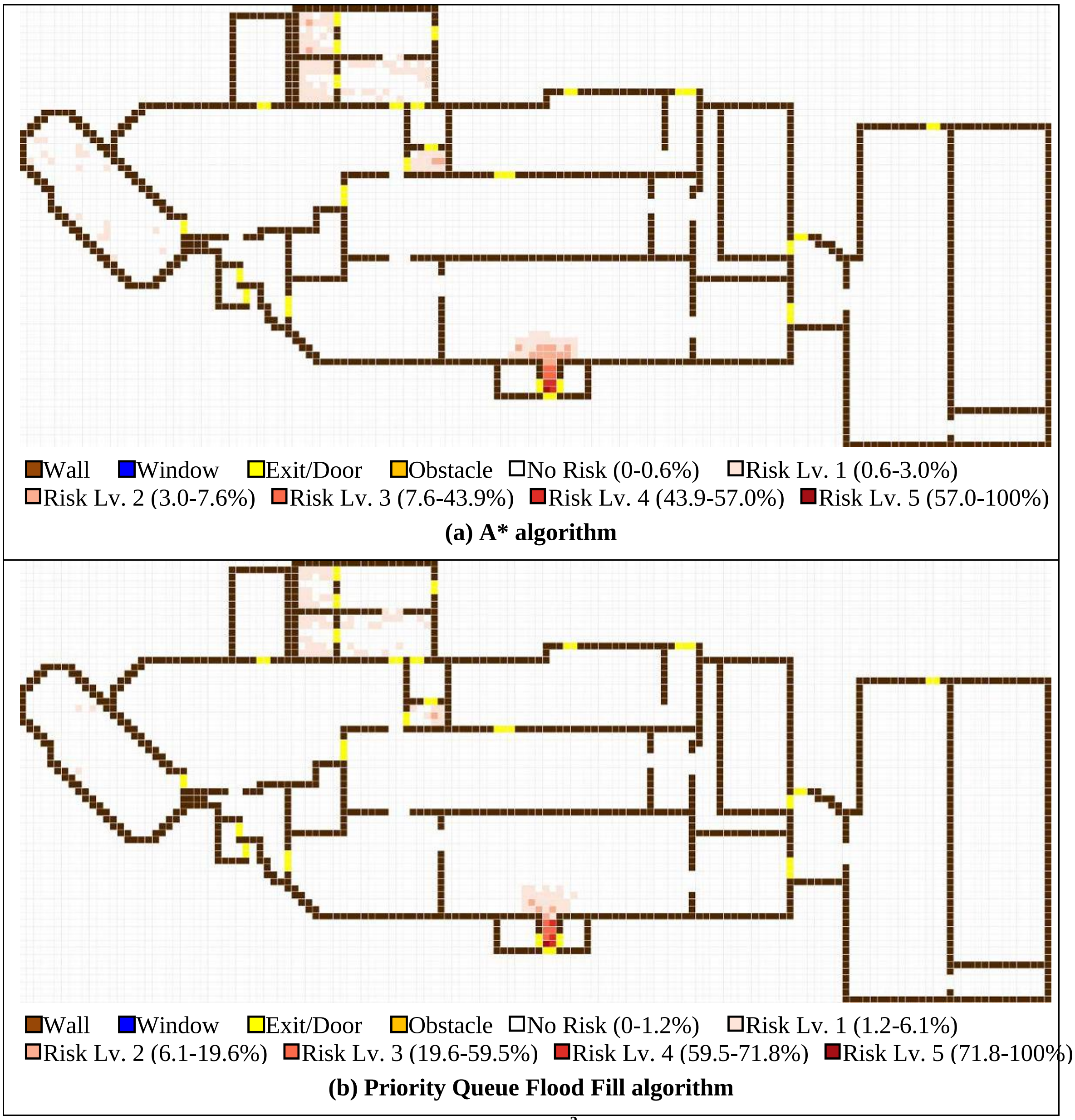
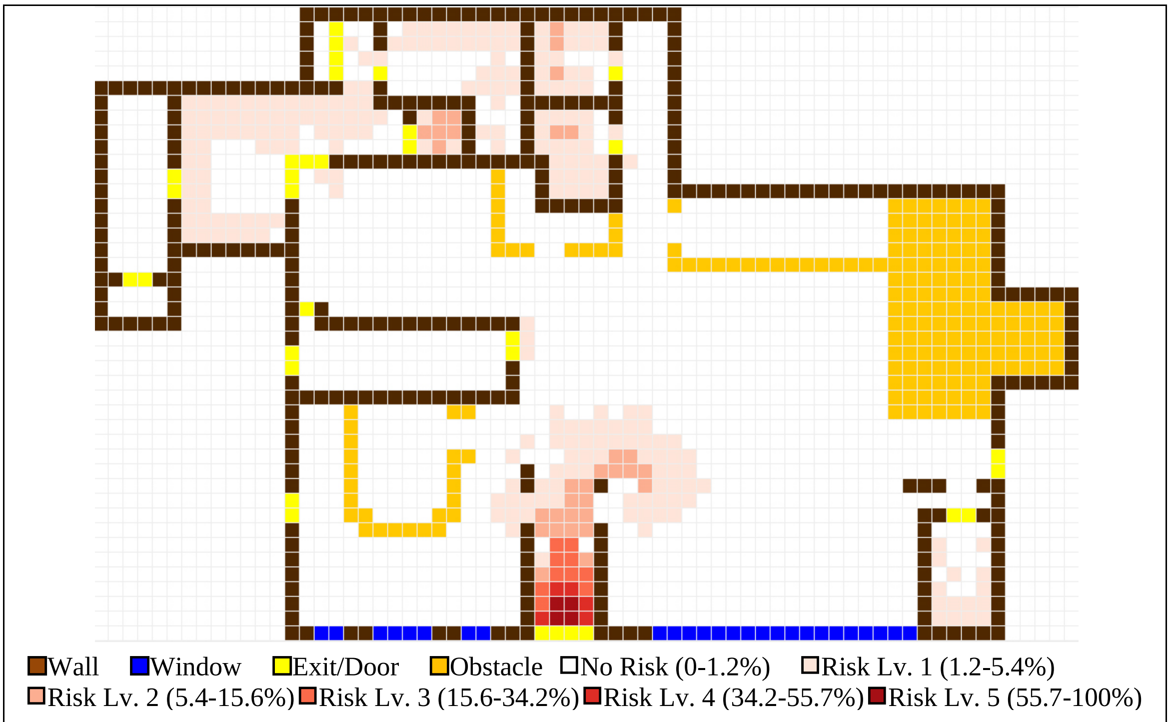


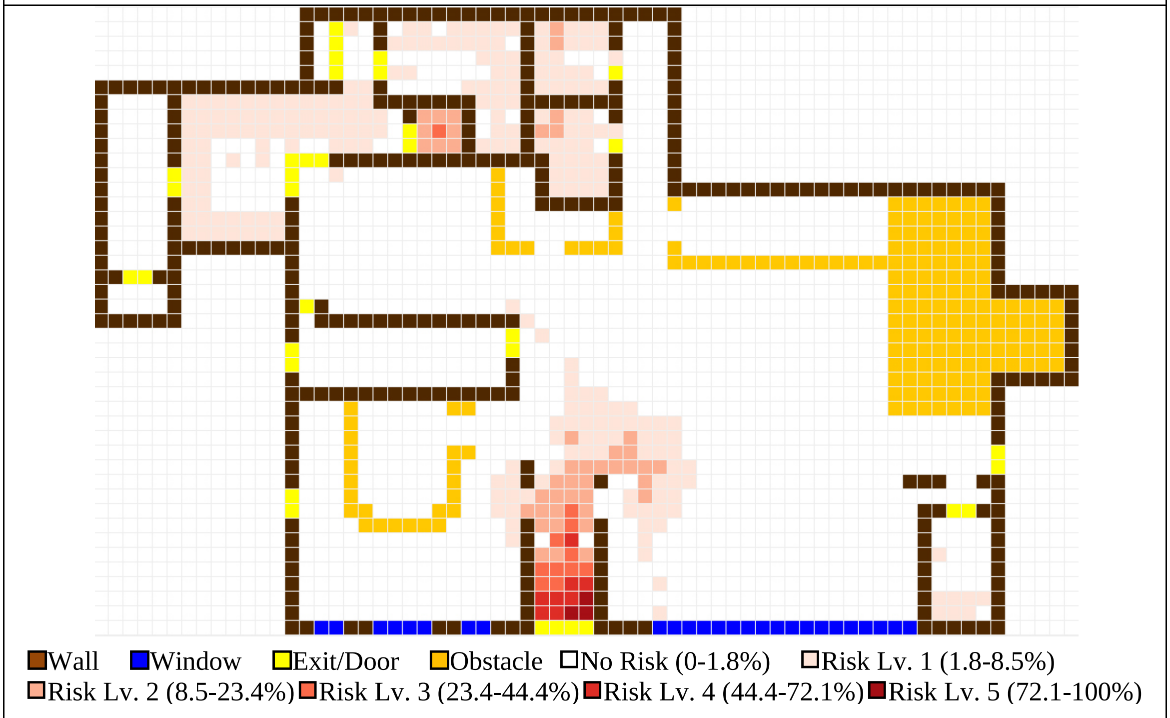
Figure D-3 The potential death locations in the 0.3 m^2 grid-based Hamlet chicken processing plant scenario.

Appendix E Distribution of Deaths in the Rhode Island Nightclub Scenarios

Scenario 1: people evacuating through kitchen exit (458 people)



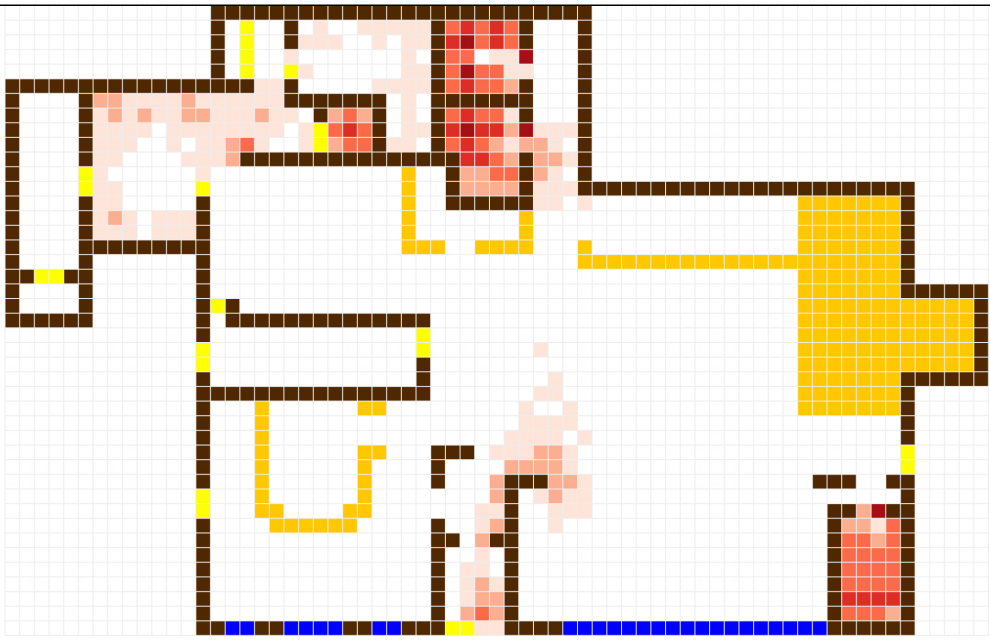
(a) A* algorithm



(b) Priority Queue Flood Fill algorithm

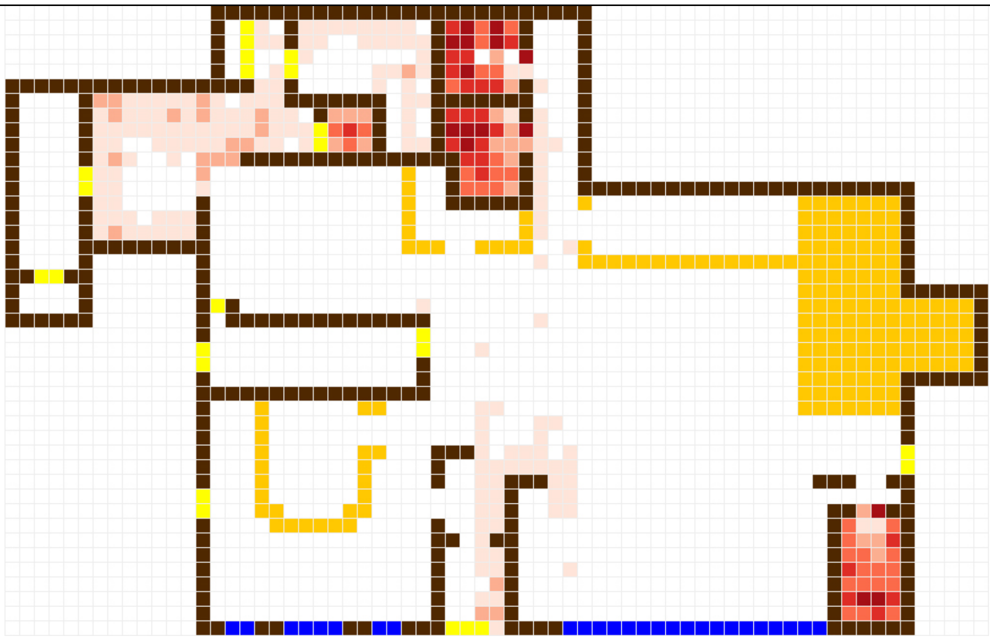
Figure E-1 The potential death locations in the Rhode Island nightclub scenario 1

Scenario 2: relocate fire origin (458 people)



Wall Window Exit/Door Obstacle No Risk (0-4.0%) Risk Lv. 1 (4.0-12.4%)
Risk Lv. 2(12.4-25.4%) Risk Lv. 3(25.4-41.2%) Risk Lv. 4 (41.2-59.3%) Risk Lv. 5 (59.3-100%)

(a) A* algorithm

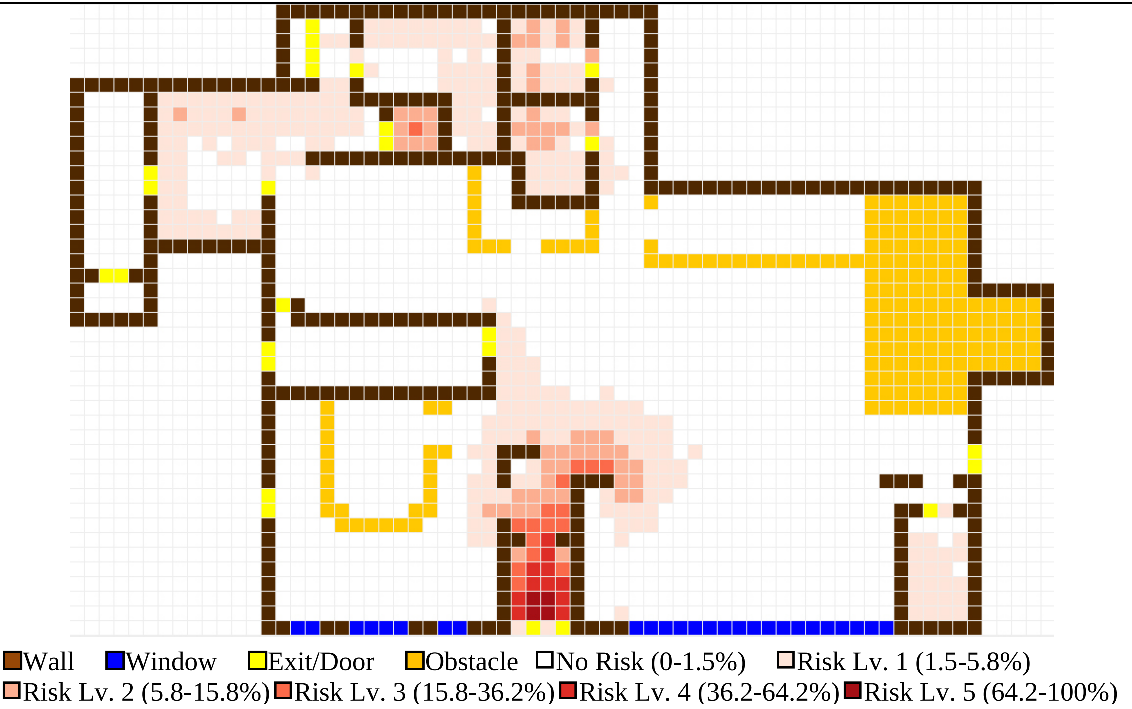


Wall Window Exit/Door Obstacle No Risk (0-3.2%) Risk Lv. 1 (3.2-12.8%)
Risk Lv. 2(12.8-27.2%) Risk Lv. 3(27.2-42.4%) Risk Lv. 4 (42.4-60.0%) Risk Lv. 5 (60.0-100%)

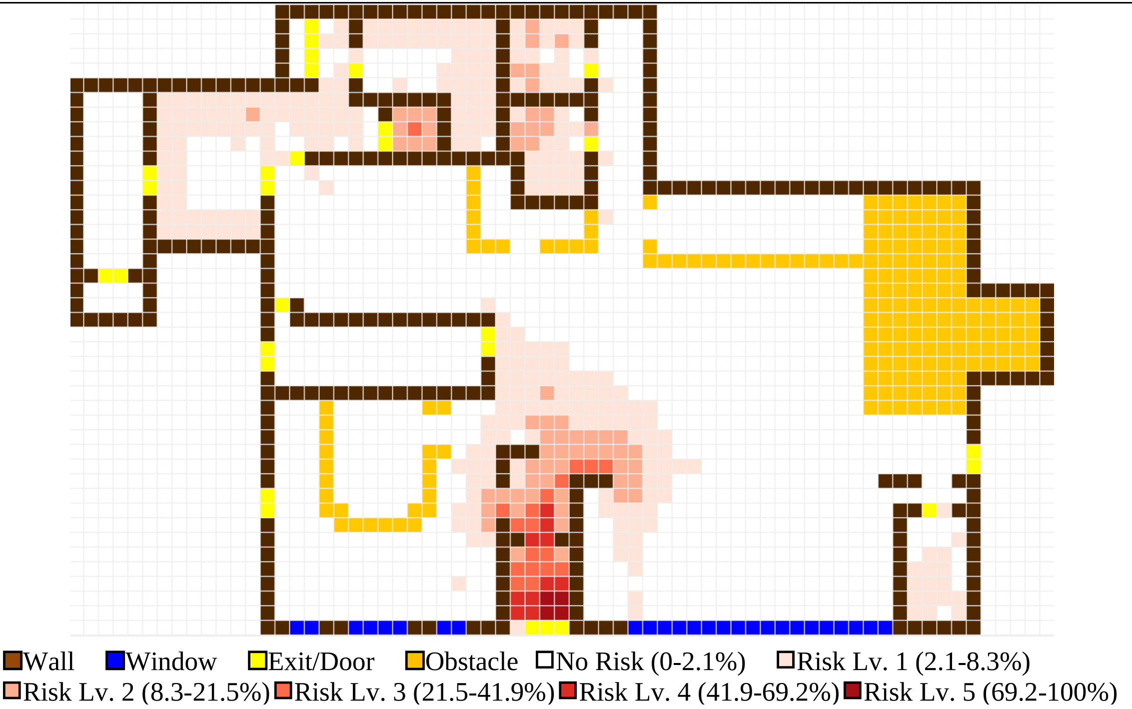
(b) Priority Queue Flood Fill algorithm

Figure E-2 The potential death locations in the Rhode Island nightclub scenario 2

Scenario 3: reduce the number of occupants without kitchen area permission (258 people)



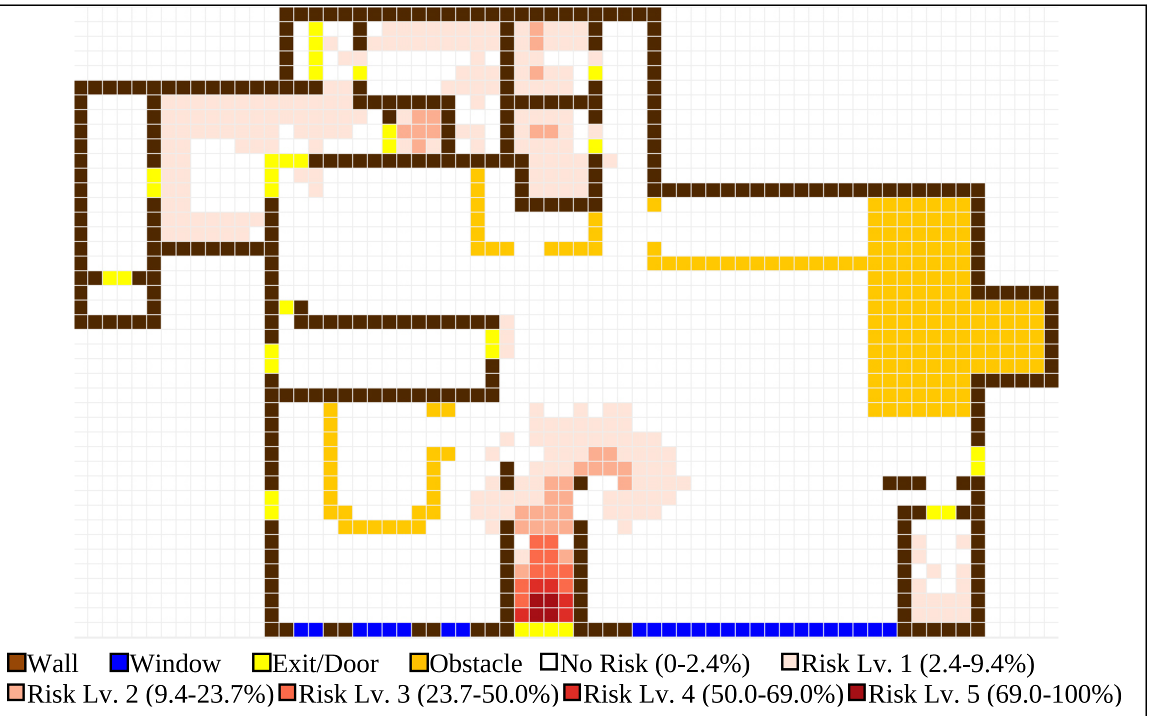
(a) A* algorithm



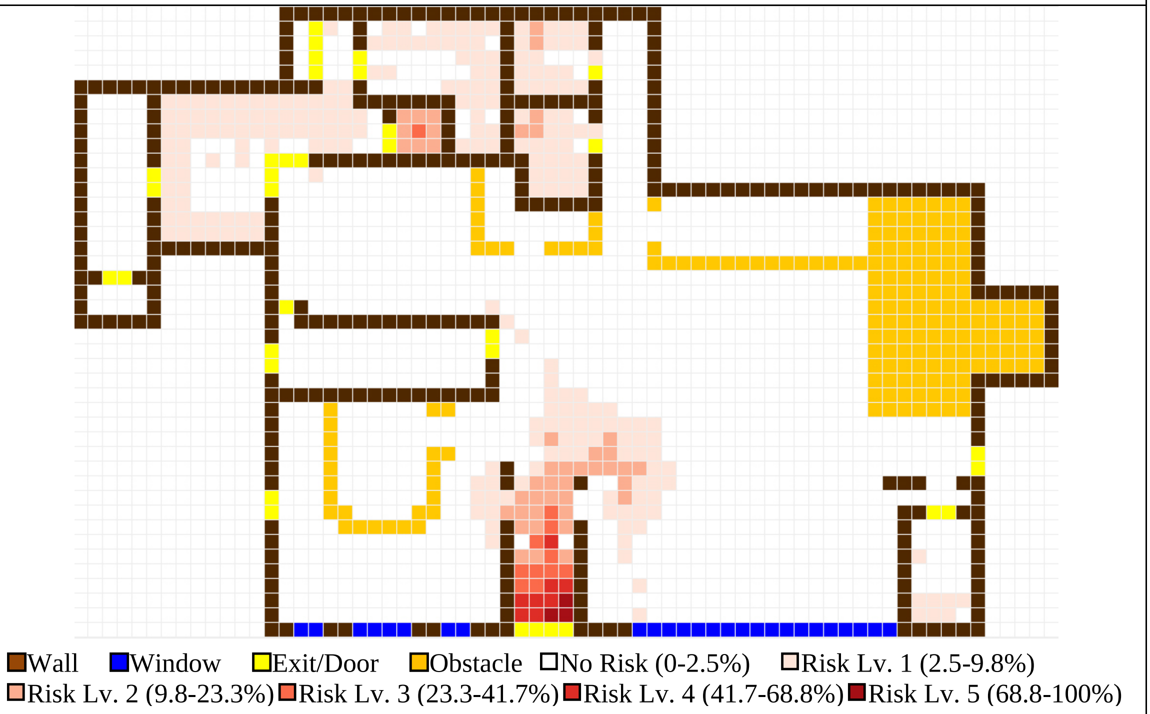
(b) Priority Queue Flood Fill algorithm

Figure E-3 The potential death locations in the Rhode Island nightclub scenario 3

Scenario 4: people evacuating through kitchen exit (258 people)



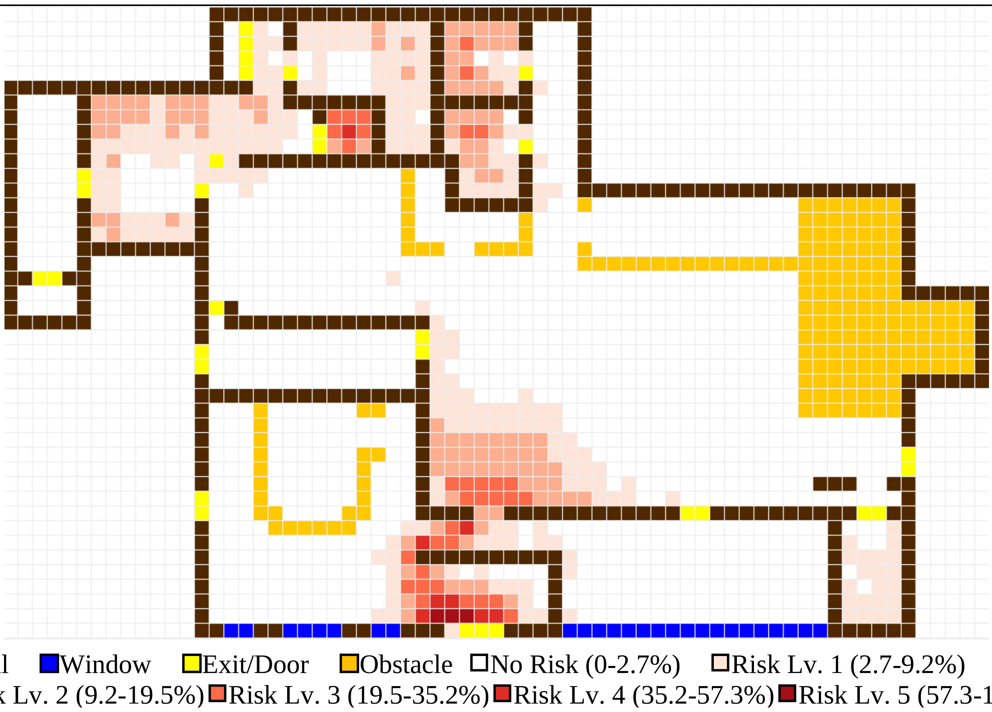
(a) A* algorithm



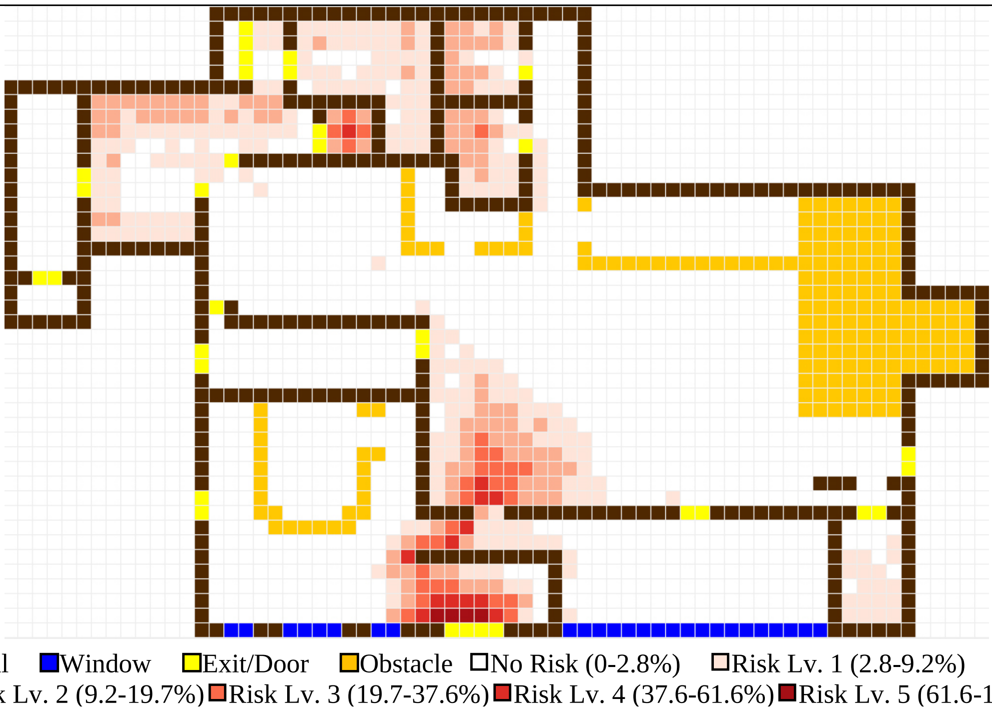
(b) Priority Queue Flood Fill algorithm

Figure E-4 The potential death locations in the Rhode Island nightclub scenario 4

Scenario 5: modify building configuration (258 people)



(a) A* algorithm



(b) Priority Queue Flood Fill algorithm

Figure E-5 The potential death locations in the Rhode Island nightclub scenario 5