



Faculty of Computer Science and Information Technology

**Mobile Crowd Steering Evacuation Model via Agent Based
Simulation by Applying the Social Force Model**

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Mobile Crowd Steering Evacuation Model via Agent Based Simulation by Applying the Social Force Model

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DECLARATION

I declare that the work in this thesis was carried out in accordance with the regulations of Universiti Malaysia Sarawak. Except where due acknowledgements have been made, the work is that of the author alone. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.



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ABSTRACT

Mobile crowd evacuation systems are cutting-edge technologies that direct and control huge masses during emergencies including fires, disasters, and terrorism. Mobile technology, usually smartphone apps, provides evacuation victims with rapid support, information, and updates. Many researchers have created simulation evacuation models to test evacuation systems' ability to optimize evacuation time. Simulation models can help policymakers evaluate evacuation plans by assessing their efficacy. In addition, simulated data can overcome the lack of genuine datasets for specific crowd situations. It overcomes the cost of capturing and pre-processing genuine crowd datasets. Famous simulation models include agent-based crowd guiding. The evaluation states that the existing agent-based steering model computes the complete set of collision-free paths with the least travel time among agents to make path decisions based on updated information. Updated information is contextual. Context includes information about an entity's context, such as its type of activity, time, location, agent velocity, and neighbouring agents' positions and velocities. The agent steering evacuation model can replicate fire evacuation, although guiding humans is untested. The current crowd simulation model describes context information, however how to simulate information dissemination in mobile crowd guiding evacuation remains unknown. As mobile crowd directing system devotes considerable attention, without such aspects it's hard to test its effectiveness. This study describes a mobile crowd evacuation simulation that effectively distributes emergency information in disaster scenarios. The agent simulation model covers all human characteristics considered for receiving evacuation messages indoors. The NetLogo-simulated agent crowd steering model includes context management, path planning, role selection, and movement modules. Using the original Social Force Model

(SFM), a benchmark result is created to validate the model. The context manager, path planning, and movement module of the original SFM were used to create the simulation model. The communication model is added to the simulation model to demonstrate the use of word-of-mouth during evacuation. A role selection algorithm chooses the leader before the evacuation. To simulate individuals following a leader during evacuation, the willingness parameter is added. Simulation models replicate victim agent and leader-follower behaviour using leader-follower models. Simulations show that grouping tactics and message forwarding increase evacuation time by 4–31%. When there are 200 to 500 evacuees, evacuation takes less time than in Chapter 3. Chapter 5 simulations show that adding the willingness parameter reduced evacuation time. In low-cooperation scenarios, the willingness parameter reduced evacuation time just slightly, suggesting little impact. The study found that evacuation is less effective when communities with weak cooperation have enough evacuation information.

Keywords: Evacuation simulation; mobile steering; crowd steering; crowd navigation.

**Model Pemindahan Pemandu Orang Ramai Bergerak melalui Simulasi Berasaskan
Agen dengan Mengaplikasikan Model Daya Sosial**

ABSTRAK

Sistem pemindahan orang ramai mudah alih adalah teknologi canggih yang mengarah dan mengawal sejumlah besar orang semasa kecemasan termasuk kebakaran, bencana, dan keganasan. Teknologi mudah alih, biasanya aplikasi telefon pintar, menyediakan sokongan, maklumat dan kemas kini yang pantas kepada mangsa pemindahan. Ramai penyelidik telah mencipta model simulasi pemindahan untuk menguji keupayaan sistem pemindahan dalam mengoptimumkan masa pemindahan. Model simulasi boleh membantu pembuat dasar menilai pelan pemindahan dengan menilai keberkesanannya. Selain itu, data simulasi boleh mengatasi kekurangan set data sebenar untuk situasi orang ramai tertentu. Ia mengatasi kos menangkap dan memproses set data orang ramai yang tulen. Model simulasi yang terkenal termasuk panduan orang ramai berasaskan ejen. Penilaian menyatakan bahawa model pandu berasaskan ejen sedia ada mengira set lengkap laluan bebas perlanggaran dengan masa perjalanan terpendek di kalangan ejen untuk membuat keputusan laluan berdasarkan maklumat yang dikemas kini. Maklumat yang dikemas kini adalah mengikut konteks. Konteks termasuk maklumat tentang konteks entiti, seperti jenis aktiviti, masa, lokasi, halaju ejen, dan kedudukan serta halaju ejen jiran. Model ejen mengarah evakuasi boleh meniru evakuasi kebakaran, walaupun membimbing manusia belum diuji. Model simulasi orang ramai semasa menerangkan maklumat konteks, namun bagaimana untuk mensimulasikan penyebaran maklumat dalam panduan evakuasi orang ramai mudah alih masih tidak diketahui. Oleh kerana sistem pengarah orang ramai mudah alih mendapat perhatian yang besar, tanpa aspek-aspek tersebut sukar untuk menguji keberkesanannya. Kajian ini menerangkan simulasi pemindahan orang ramai mudah alih

yang mengagihkan maklumat kecemasan secara berkesan dalam senario bencana. Model simulasi ejen merangkumi semua ciri manusia yang dipertimbangkan untuk menerima mesej pemindahan di dalam bangunan. Model kawalan kawanan ejen simulasi NetLogo termasuk pengurusan konteks, perancangan laluan, pemilihan peranan, dan modul pergerakan. Menggunakan Model Kekuatan Sosial (SFM) yang asal, hasil penanda aras dicipta untuk mengesahkan model tersebut. Pengurus konteks, perancangan laluan, dan modul pergerakan SFM asal digunakan untuk mencipta model simulasi. Model komunikasi ditambahkan ke model simulasi untuk menunjukkan penggunaan penyebaran dari mulut ke mulut semasa pemindahan. Algoritma pemilihan peranan memilih ketua sebelum pemindahan. Untuk mensimulasikan individu mengikuti pemimpin semasa pemindahan, parameter kesediaan ditambah. Model simulasi meniru tingkah laku ejen mangsa dan pemimpin-pengikut menggunakan model pemimpin-pengikut. Simulasi menunjukkan bahawa taktik pengumpulan dan pengiriman mesej meningkatkan masa pemindahan sebanyak 4–31%. Apabila terdapat 200 hingga 500 orang yang dipindahkan, pemindahan mengambil masa yang lebih singkat berbanding dalam Bab 3. Simulasi Bab 5 menunjukkan bahawa penambahan parameter kesediaan mengurangkan masa pemindahan. Dalam senario kerjasama rendah, parameter kesediaan hanya mengurangkan masa pemindahan sedikit, menunjukkan sedikit impak. Kajian mendapati bahawa pemindahan kurang berkesan apabila komuniti yang mempunyai kerjasama yang lemah mempunyai maklumat pemindahan yang mencukupi.

Kata kunci: Simulasi pemindahan; pemanduan mudah alih; pemanduan orang ramai; navigasi orang ramai

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LIST OF ABBREVIATIONS

AI	Artificial Intelligence
BDI	Belief-Desire-Intention
DV	Desired Velocity
RFID	Radio Frequency Identification
SFM	Social Force Model
SIC	Social Interaction with Communication
USA	United States of America
VR	Virtual Reality
WOM	Word-of-Mouth

CHAPTER 1

INTRODUCTION

1.1 Introduction

A natural or manmade disaster has made the city or municipality more aware of the importance of evacuation management. One aspect of evacuation management is to provide an emergency plan based on the building plan. An emergency plan is essential for controlling crowds in emergencies to ensure quick and safe evacuation (Shiwakoti et al., 2020).

Every building structure has its pre-defined emergency plan for how occupants should exit the facility during an emergency. However, in an emergency, fire or smoke could obstruct any passageways, resulting in fatalities if the individuals trying to flee the building do not know other routes (Zuallkernan et al., 2019). In this situation, a fixed evacuation plan or poorly managed evacuation plan is not even remotely acceptable and must thus undergo significant revision regularly to avoid harmful events (Alexander, 2017).

In line with the latest technological developments, emergency evacuation is assisted by smart devices. These applications are designed so that people can quickly locate themselves inside the building and receive straightforward evacuation instructions. The common goal of using the mobile evacuation assistance application is to lessen or prevent injuries among evacuees by guiding them safely to the nearest exit. For instance, the use of mobile applications and dynamic digital signage are two of the many approaches that are now being researched as potential ways to aid

evacuees. At the same time, they are being evacuated (Hsu et al., 2014). The system is a mobile-assisted evacuation application or crowd evacuation system. The mobile crowd evacuation system significantly improved the whole evacuation procedure to the point where it reduced the number of trapped evacuees by supplying them with real-time information regarding safe evacuation routes to follow (Atila et al., 2018).

Various mobile applications have been developed to assist people in evacuating open spaces (e.g., underground hubs, stadiums) or indoor spaces (e.g., buildings) during an emergency. Some examples are Transportation Hubs Guiding Application (SAVE ME) (Panou et al., 2013), Intelligent Active Alert Application (Wu et al., 2013), Educational Trip Support System (Kasahara et al., 2014), Personalized Alert Notifications and Evacuation Route (Aedo et al., 2012), Safe Together (Pattath et al., 2010) and SMS-based route generation system (Regalado et al., 2013), EasyFind (Chen & Liu, 2019), location-based evacuation system (Choi et al., 2021), CellEVAC System (Lopez & Garcia, 2022), smartphone voice-guided evacuation system (SVGES) (Kuo. et al., 2022), IoT based smart, intelligent evacuation guidance system (Mohammadiounotikandi et al., 2023). These applications allow the evacuees to receive personalised evacuation instructions. For example, evacuees can report the type of emergency (Pattath et al., 2010), thus appropriate safety instruction can be delivered.

Based on the reviews, the mobile crowd evacuation system generates evacuation routes based on the present data sent to the central system (Zualkernan et al., 2019; Chen & Liu, 2018). Meanwhile, the evacuation instructions should consider certain circumstances limiting users' ability to comprehend the messages (e.g., long

text instruction). For example, precise language is used (Aedo et al., 2012) to reduce the time needed for comprehension, and the action in question can be carried out immediately. In addition, some studies have been done that combine the text, image, and voice components of the evacuation instructions (Kuo et al., 2022).

The overview of the system flow is as follows. First, the system will receive the location of hazards from the sensors located in the building. The victims will be updated on their current location in the system. From the pre-defined safe evacuation route, the system will generate the paths to the exit door from the victim's current location and deliver them as graphical instructions. The information to be received by victims is straightforward to minimise the time taken to evacuate the building. In this case, the system can identify a clear route to avoid congestion at potential bottlenecks inside the building.

Although mobile crowd evacuation systems have been developed, testing those applications in a natural environment is time-consuming and cost-consuming. In addition, it is challenging to replicate real-world scenarios (Pattath et al., 2010) and ensure the safety of test subjects during large-scale evacuation. As the evacuation requires many people to move towards exits, the difficulties of receiving such a big crowd must be handled. Meanwhile, coordinating and getting support from the masses is a trivial task.

Due to the testing difficulty, crowd simulation is introduced to study the crowd situation at various events such as mass gatherings at holy places (Al-Ahmadi et al., 2021; Owaidah et al., 2019), terrorist attacks (Song et al., 2022; Lu et al., 2020), subway (Qin et al., 2020), just named a few. The authorities can better prepare for any

potential emergency evacuations required during the big event by using crowd simulation. In addition, the authorities can organise the evacuation route according to the circumstances to reduce the number of injuries and prevent fatalities. Although crowd simulation has received much attention to date, how to simulate mobile crowd evacuation systems, primarily through agent-based modelling and simulation, is yet to be explored.

In this study, simulation can become the technique to study mobile crowd evacuation systems. However, there is insufficient work to design and develop a simulation model, especially for mobile crowd evacuation systems. An agent-based crowd steering model for simulating a mobile crowd evacuation system based on the following criteria is invented in this research. The model covers the spectrum of human criteria upon receiving evacuation guidance messages in an indoor area. Accordingly, the model focus on social settings and social structures as contextual information. Meanwhile, the model defines the leader or follower role when deciding on the evacuation decision. On the other hand, willingness to evacuate is the parameter we introduce when handling the message. In addition, the guidance message is designed based on the context information.

1.2 Problem Statement

Mobile crowd evacuation systems are cutting-edge technologies specifically developed to direct and control large groups of people during critical circumstances like fires, catastrophic events, or acts of terrorism. These systems utilise mobile technology, typically through smartphone applications, to deliver immediate assistance, information, and updates to persons in evacuation situations. Numerous academics

have constructed simulation evacuation models to investigate the efficacy of evacuation methods in optimizing the overall evacuation time. Among a famous simulation model is agent-based crowd steering simulation. From the review, the current agent-based steering model involves compute from the complete set of collision-free paths with least travel time among individual agent to make path decision based on received updated information among agents. The updated information further defined as contextual information by Ibrahim et al. (2018). According to Ibrahim et al. (2018), context is any available information useful for describing situation of an entity such as individual, type of activity, time and location, agent's velocity and other neighbouring agents' position and velocities. While the agent steering evacuation model can simulate fire evacuation, how to simulate guiding the people during evacuation is yet to explored. Although context information is described in latest crowd simulation model by Ibrahim et al (2018), how to model the spreading of information in mobile crowd steering evacuation is yet to explored. As mobile crowd steering system is paying much attention, without those elements, we argue that it is hard to test the effectiveness of current mobile crowd steering system. Hence, there is a need to explore a new agent-based simulation model for a mobile crowd evacuation system.

1.3 Significance of Research

This study aims to solve the problem of to simulate a mobile crowd steering during an evacuation. The study introduces an agent-based crowd steering simulation model which can model a situation in which people are holding smartphones, exchanging messages, and model a human willingness to follow the leader during the evacuation. In addition, the developed model through NetLogo able to simulate what-

if scenario. The NetLogo simulation results are important for policy maker when designing a mobile guiding system during evacuation.

1.4 Research Questions

This study seeks to address the research questions outlined in the research objectives:

- i. What are the elements in designing an agent crowd steering simulation model by building on the of state-of-the-art agent crowd simulation model, social force model, for mobile crowd steering system?
- ii. How to evaluate the effectiveness of the proposed agent crowd steering simulation model through simulating a mobile crowd steering system?

1.5 Research Hypothesis

The research hypothesis for this study is Social Force Model (SFM) need to be equipped with role selection, communication and willingness to follow the leader during the evacuation in order to support mobile crowd steering.

1.6 Objectives

The objectives of this study are the following.

- i. To design and develop an agent crowd steering simulation model for mobile crowd steering evacuation simulation based on the social force model extension.
- ii. To analyse the effectiveness of the proposed agent simulation model.

1.7 Scope of The Research

This study centres on utilising the Social Force Model as the basis for the agent crowd steering simulation model in the context of evacuation scenarios. The Social Force Model is one of the famous movement models and also known as crowd steering model to simulate crowd evacuation (Min Zhou et al., 2019). This research aims to simulate the evacuation using a room layout design that accommodates a maximum of 500 victim agents. The experiments will be performed to assess the efficacy of the suggested architecture, which utilises the Social Force Model, compared to the expanded model, which includes the agentmessaging model, agent's willingness, and the leader-follower model. This research is restricted to evaluating the proposed model in a controlled experimental environment.

1.8 Thesis Structure

This thesis is organised into six chapters: Chapter 1) Introduction, Chapter 2) Literature Review, Chapter 3) A Simulation Evacuation Model, Chapter 4) The Agent Messaging Model, Chapter 5) The Willingness of Agent and Leader-Follower Behaviour, and 6) Conclusion and Future Work. Brief descriptions of the content of each chapter are given as follows:

Chapter 1 of the thesis begins with a discussion on the problem statements, significances of research, research questions, research hypothesis, objectives, and contributions of the research topic.

Chapter 2 highlights the mobile crowd evacuation system and discusses the existing approaches in agent-based crowd steering simulation. This chapter also discusses the agent crowd steering behaviours studies.

Chapter 3 describes the proposed agent simulation model for mobile crowd simulation. This chapter includes a detailed description of the model design. The outcomes of the simulation evacuation model are analysed in detail and form the benchmark for the rest of the experiment in Chapter 4 and Chapter 5.

Section 4 provides a comprehensive explanation of the agent messaging model, which is seamlessly included in the proposed simulation evacuation model. The model simulates the capacity of a victim agent to spread messages. The analysis and comparison of the simulation model's outcome with the benchmark result, established in Chapter 3, is conducted.

Chapter 5 provides a detailed explanation of the revised Social Force Model, which incorporates the willingness parameter and leader-follower behaviour. A comprehensive description is provided of the victim agent's willingness to adhere to the leader. The analysis and comparison of the simulation result is conducted in comparison with the results generated in Chapter 3.

Chapter 6 concludes the thesis and describes contribution, several limitations, challenges, and potential future works.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter reviews the mobile crowd evacuation system and the background knowledge of this research. Section 2.2 presents the mobile crowd evacuation system. Section 2.3 explains the agent-based crowd steering for evacuation study. Section 2.4 describes the agent crowd steering behaviour studies. Section 2.5 describes the crowd steering simulation approaches, while Section 2.6 presents the discussion of the literature review. Finally, Section 2.7 presents the chapter summary.

2.2 Mobile Crowd Evacuation System

The natural disasters that occurred in the past decades have attracted several studies on disaster prevention and mitigation to minimise fatalities and damages. Among them, crowdsourcing systems are introduced in emergency evacuation to support the actions of the emergency and rescue services team and volunteers, especially in time-critical situations. The emergency response plan is a significant element that needs to be strictly followed during the emergency to handle the unexpected event. For example, a crowd of people in a panic state will struggle to reach safety as quickly as they can. Therefore, this panic often leads to pushing and stampedes, which can cause significant injuries.

The recent technological advancements of smartphones and smart wearable devices have attracted great attention to the study of crowd evacuation using assisted mobile applications. These applications are designed so that people can quickly

determine their location within the building and receive straightforward evacuation instructions. The common goal of using the mobile evacuation assistance application is to lessen or prevent injuries among evacuees by guiding them safely to the nearest exit.

Various mobile applications have been introduced to assist people in evacuating openspaces (e.g., underground hubs, stadiums) or indoor spaces (e.g., buildings) during an emergency. Some examples are Transportation Hubs Guiding Application (Panou et al., 2013), Intelligent active alert application (Wu et al., 2013), Educational Trip Support System(Kasahara et al., 2014), Personalized Alert Notifications and Evacuation Route (Aedo et al.,2012), Safe Together: A mobile guidance system (Pattath et al., 2010) and SMS-based route generation system (Regalado et al., 2013). These applications allow the evacuees to receive personalised evacuation instructions. For example, evacuees can report the type of emergency (Pattath et al., 2010), thus appropriate safety instruction can be delivered.

While the development of previous works is no much updated, there is an emerging of mobile guide system for evacuation to date. According to Zhou et al (2019), the guided crowd evacuation system is emerging using advanced monitoring techniques, AI techniques, computer technology, and intelligent inducting algorithms. For example, intelligent evaluation guidance system for large building is developed by Wu et al (2016). The evacuation guiding system is based on computer vision technology, RFID based networking technology to guide the user through mobile phone during evacuation. A mobile guidance system for evacuation is developed based on microcontroller Wi-Fi board and node architecture-based system (Raju et

al., 2019). Safe route, a mobile application based intelligent and personalized fire evacuation system is introduced by Hayes et al. (2021).

When developing a personalised guide system, evacuation instructions should consider certain circumstances limiting users' ability to comprehend the messages (e.g., longtext instruction). As a result, many applications, including Save Me (Panou et al., 2013), Intelligent Active Alert (Wu et al., 2013), and Educational Trip Support System (Kasahara et al., 2014), have begun incorporating sign-based instructions. An example of sign-based instruction is colour-coded instructions (Wu et al., 2013), designed to assist evacuees in quickly comprehending the instructions rather than reading a lengthy text evacuation instruction. Aside from that, precise language is used (Aedo et al., 2012) to cut down on the amount of time needed for comprehension, and the action in question can be carried out rightaway.

In addition, some studies have been done that combine the text, image, and voice components of the evacuation instructions (Kuo et al., 2022). Figure 2.1 shows some mobile interfaces of the intelligent; active alert application introduced by (Aedo et al., 2012). This application provides a building floor plan that enables the user to understand the building layout quickly and locate the current position. A warning message is sent to the user's mobile device that contains instructions to be followed during evacuation. Another feature this application offers is different colour-coded arrows that indicate the distance between the user and the exit door. Colour-coded instruction is easy to follow as little time is required to understand the directions during a time-limited emergency.

Although mobile crowd evacuation systems have been successfully developed, most of the studies do not reflect the actual deployment of the entire solution or technology. Indeed, most of the system evaluation is either missing the evaluation step or use a real evacuation study. It has been reported that conducting a real evacuation is time- and cost-consuming. In addition, the evacuation only able to cover a limited number of participants. Table 2.1 shows the number and type of participants engaged during the testing process of mobile crowd applications, while Table 2.2 shows the instruction format of evacuation plans, evaluation techniques, and evacuation scenes. It can be concluded that many existing studies in mobile crowd evacuation applications involved few participants during the evaluation process. Meanwhile, coordinating and getting the crowd support is a crucial task in a real-world evacuation studies.

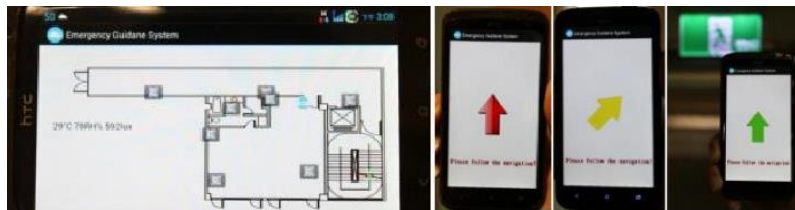


Figure 2.1: Intelligent Active Alert Application (Aedo et al., 2012)

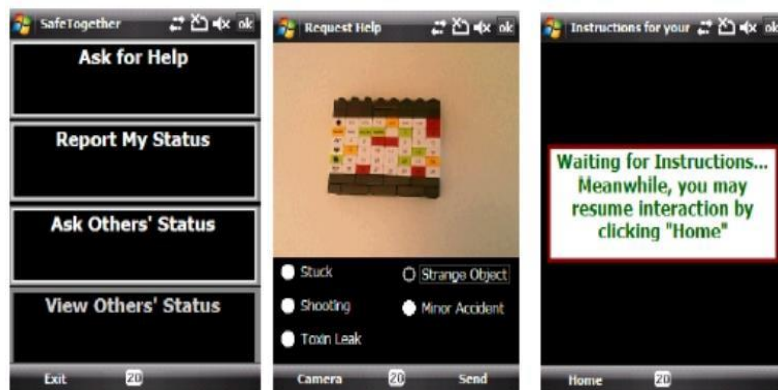


Figure 2.2: Features in Safe Together Application (Pattath et al., 2010)

Table 2.1: The Number of Participants Involved in Application Evaluation Testing

Mobile Application	Number of Participants	Type of Participants	Author
SAVE ME	24	1. Elderly 2. Wheel chair 3. Commuters	Panou et al. (2013)
Intelligent Active Alert	Not reported	Not Mentioned	Wu et al. (2013)
Educational Trip Support System	8	1. Teachers 2. Students	Kasahara et al. (2014)
Personalised Alert Notifications and Evacuation Route	12	Postgrads students	Aedo et al. (2012)
Safe Together	9	Not Mentioned	Pattath et al. (2010)
BahaBa	30	Not Mentioned	Regalado et al. (2013)
Location-aware application	11	Age 20 to 26	Chittaro and Nadalutti (2008)
TECuidamos	Not Mentioned	Not Mentioned	Lopez-Caudana et al. (2022)
SVGES	26	Age 20 to 50	Kuo et al. (2022)
Intelligent evaluation guidance system for large building	Not Mentioned	Not Mentioned	Wu et al. (2016)
Mobile guidance system	Not Mentioned	Not Mentioned	Raju et al. (2019)

Table 2. 1: continued

Safe route	Not Mentioned	Not Mentioned	Hayes C. (2021)
Intelligent evacuation guidance system	16	Age 28 to 47	Balboa, A. (2020)

Table 2.2: The Instruction Format of the Evacuation Plan

Mobile Application	Instruction Format	Evaluation	Evacuation Scene
SAVE ME	Sign-based	Simulated fire alarm	Indoor
Intelligent Active Alert	Sign-based	Simulated fire alarm	Indoor
Educational Trip Support System	Sign-based	Quantitative Survey	Outdoor
Personalised Alert Notifications and Evacuation Route	Text, map, 3D view	Simulated fire alarm	Indoor
Safe Together	2D map	Qualitative study	Indoor
BahaBa	Text-based	Survey	Indoor
Location-aware 3D application	3D viewmap	Simulated fire alarm	Indoor
TECuidamos	2D viewmap	Computer simulation	Indoor
SVGES	Text-based, voice, and image	Simulated fire alarm	Indoor

Given the challenges encountered to understand the mobile crowd evacuation system testing, this thesis proposes employing agent-based simulation to model and simulate mobile crowd evacuation systems. This thesis contends that leveraging existing agent-based crowd steering techniques to simulate mobile crowd evacuation systems is reasonable.

Agent-based simulation is well known on computer system testing. For example, the agent-based simulation is used on network simulation in simulating network traffic and protocols to test network performance and security. On the other hand, agent-based simulation is used in simulating traffic flow and control systems to test traffic management algorithms (Onggo et al., 2016; Liubovic et al., 2009).

2.2 Agent-based Crowd Steering for Evacuation Study

Crowd steering is introduced to secure the egress of the crowd during an emergency at mass gathering areas or events, has become the interest of many researchers until the present day (Still et al., 2020; Owaidah et al., 2019; Murakami et al., 2020). Handling the crowd during an emergency is highly challenging due to unpredictable panic behaviour that may emerge during evacuation among the crowd (Wang et al., 2022; Sahin et al., 2019). During the emergency evacuation, the crowd may behave aggressively, such as pushing other people (Helbing et al., 2002), walking in disorder, moving faster (Helbing et al., 2002), or even becoming self-focused (Tubbs & Meacham, 2007), which increases along the way to the exit door. Self-focused behaviour worsens the situation because the victims become less

socially able to decide on the best route to escape. These emergent behaviours could cause injuries or even death.

Agent-based crowd steering is built upon agent models. Agent-based models are computer models that attempt to recreate the actions and interactions of people (the agents) inside a specific setting (Sahin et al., 2019; Kremer et al., 2021). In comparison to older paradigms such as object-oriented, it is anticipated that the agent-based model is outfitted with elements such as autonomy, sociality, reactivity and proactivity, and communicative and cooperative capacities will provide better functionality and a higher quality overall (Loeser et al., 2021). Agent-based modelling is being used in a variety of research fields, including the simulation of disease transmission (Datta et al., 2022; Cuevas, 2020) and crowd simulation (Clay et al., 2021; Van Toll et al., 2021), as well as transportation planning (Zwick et al., 2021; Shen et al., 2018), business modelling (Poledna et al., 2023; Bertani et al., 2021), and modelling of crowds (Zia & Ferscha, 2020; Trivedi & Pandey, 2020).

Agent-based crowd steering becomes a huge focus as it can model heterogeneous individuals. The heterogeneity of a crowd plays a significant role in crowd control (Park et al., 2015). Furthermore, the flexibility of the agent-based model has made it easy to include various behavioural factors (Zhong et al., 2015). An agent is constantly executing queries to the environment database to obtain sensory information such as events, objects and other agents (Park et al., 2015). Then, the agent will construct knowledge related to present occurrences through a reasoning mechanism. An agent keeps a short-term working memory related to past occurrences.

Finally, an agent decides to achieve its goal according to current status and past occurrences in the memory.

The purpose of agent-based modelling is to simulate the behaviour of autonomous agents within a complex system to generate self-organisation as a result of the interaction between agents. In agent-based modelling, the agents are modelled in such a way that they can interact with each other within their situated environment and eventually produce self-organising behaviour such as walking in line, queuing, and forming a group. This allows the agents to simulate real-world behaviours like walking in line, queuing, and forming a group.

Agent-based crowd steering entails the study of agent motion modelling. Steering sits between cognition and locomotion on the hierarchy of intelligence layers. Steering is a result of complex processes which involve interactions between agents (Patil et al., 2011). Steering involves many parameters, such as the agent's velocity, collision prediction and environmental information. These parameters are frequently changing (dynamic) and could affect the paths to the exit door. Thus, real-time constraints increase the complexity of the process (Oliva & Vilhjálmsson, 2014). In other words, steering is a complex process, and there is no specific and precise solution to achieve the expected results (Ozcan et al., 2019).

During an evacuation, crowd steering controls and manages the crowd by communicating information regarding the evacuation route. The evacuation routes are generated by some algorithms that consider the parameters related to the evacuees, environment, and hazards. The purpose of varying a parameter in crowd steering simulation research (in this case, who and what instructions people get, if any) and

seeing how it influences the outcome of the simulation (which is a measurable value in the simulation, e.g., the time or average time it takes to for each person to leave the building in case of an emergency).

Decision-making is very important to achieve a successful evacuation process with no injuries or fatalities. However, decision-making could be influenced by crowd behaviour. For example, an evacuee follows a large group of people during evacuation. However, the crowd behaviour could be unpredictable and varies in case of high stress during critical hazards that will cause more injuries. Thus, social interaction between evacuees significantly affects decision-making during evacuation. Hence, various strategies have been introduced to model and simulate the crowd steering agent behaviour.

2.3 Agent Crowd Steering Behaviour Studies

The history of steering behaviour dates back to 1987 when Reynolds (1987) introduced 25 steering behaviours for autonomous characters, opening many research opportunities. Some of these behaviours could be combined to achieve specific tasks. For instance, flocking is a combination of alignment, cohesion, and separation steering behaviours.

The common goal of steering is reaching a destination while avoiding collision. There are two types of steering: local steering and global steering. Local steering involves local motion that requires agents to access some local information (i.e. agent's velocity and distance of nearby agent) to perform collision avoidance of agent-to-agent and agent-to- static objects. Global steering uses global information

(i.e. crowd density and hazard location) to compute the global navigation paths for each agent from its initial position to the destination. The data is stored in the knowledge base for future retrieval. Local and global steering is combined to create a practical evacuation model that produces a safe and efficient evacuation path. The steering algorithm must consider both local and global planning so that agents can safely move towards their destination. Typically, for complex and large building space, evacuees become unaware of available paths that are feasible for evacuation because of insufficient knowledge about the internal structure and connectivity of the rooms. Thus, the problem causes a delay in the evacuation process (Liu et al., 2018).

The existing steering approaches vary from one another according to their primary purpose. The common methods are based on finding the nearest exit based on the shortest path, using Dijkstra's algorithm as in Rahman et al. (2008), Wu et al. (2013), Patil et al. (2011), Chen and Feng (2009), Tsai et al. (2018), Shendarkar et al. (2008), Qiu and Hu (2010), Guy et al. (2010) or using A* pathfinding algorithm as in Foudil et al. (2009), Kalaet al. (2018), Juniastuti et al. (2016), Oliva and Vilhjálmsson (2014), Rojas et al. (2013), Van Toll et al. (2012) and Sud et al. (2007b). The environment may consist of some obstacles, either static (i.e., wall, furniture) or dynamic (i.e., other agents); thus, steering should involve collision avoidance to ensure the safe navigation of agents from the initial position to the goal position. However, steering agents in crowded environments is very challenging due to the highly dynamic environment. The agent needs to be updated on the position, velocity, and heading of other agents to minimise the congestion that could occur in some potential bottleneck areas. Typical steering approaches in evacuation contexts are not for highly dynamic contexts where the paths given to people could change over time.

Paths given to people should be dynamic so they can adapt to surrounding situations to ensure optimum safety for all people.

From the review, in Table 2.3, this thesis classifies the agent steering behaviour into eight categories. They are the shortest path approach, prediction approach, context-aware, social-based, behaviour-based, learning, collision avoidance, and optimisation approach.

Table 2.3: Summary of The Crowd Steering Behaviour for Agent

Author / Country	Approach
Hu et al. (2023) - USA	Learning Approach
Ozcan et al. (2019) – Turkey	Time-based density information
Aroor et al. (2018) – USA	Bayesian online-learning
Liu et al. (2018) – China	Knowledge-based
Kala (2018) – India	Probabilistic roadmap
Rösmann et al. (2017) - Germany	Timed elastic bands
Tsai et al. (2018) – Taiwan	Guidance path
Vemula et al. (2017) – USA	Velocity modelling
Weiss et al. (2017) – USA	Position-based
Dutra et al. (2016) – Brazil	Gradient-based
Godoy et al. (2016a) – USA	C-Nav
Godoy et al. (2016b) – USA	Bayesian Inference
Fang et al. (2016) – USA	Scalar field method
Juniastuti et al. (2016) - Indonesia	Reciprocal Velocity Obstacles
Kremyzas et al. (2016) - Netherlands	Extended Social Groups and Navigation (SGN)
Luo et al. (2017) – China	Gap Seeking proactive steering

Table 2.3: continued

Zhao and Winter (2016) - Australia	Fading memory model
Van Toll et al. (2015) - Netherlands	Explicit corridor map
Niu et al. (2015) – China	Dynamic decision making
Zhong et al. (2015) - Singapore	Segmentation strategy
Oliva and Vilhjálmsson (2014) - Iceland	Social intentions and movements prediction
Rojas et al. (2013) – Korea	Two-level steering
Hou et al. (2014) – China	Improved Social Force Model
Hu et al. (2013) – Singapore	Patterned-based approach
Duives and Mahmassani (2012) - Netherlands	Discrete Choice Model
Van Toll et al. (2012) - Netherlands	Density-aware
Fang et al. (2011) – China	Ant Colony
Viswanathan and Lees (2011) - Singapore	Information-based perception model
Van den Berg et al. (2011) - USA	Acceleration-velocity obstacle (AVO)
Patil et al. (2011) – USA	Goal-directed navigation
Ondrej et al. (2010) – France	Synthetic vision-based
Guy et al. (2010) – USA	Principle of Least Effort
Qiu and Hu (2010) – USA	Shortest Path
Schuerman et al. (2010) - USA	Situation Agent
Narain et al. (2009) – USA	Aggregate Dynamics
Chen and Feng (2009) - Singapore	Fast flow control algorithm
Shi et al. (2009) – China	Physical System Dynamical Model
Foudil et al. (2009) – France	Cell decomposition
Xiong et al. (2009) - Singapore	Rule-based motion planning
Shendarkar et al. (2008) - USA	VR-based BDI
Lin et al. (2008) - USA	Precomputed map
Sud et al. (2007a) – USA	Multi-agent Navigation Graph (MaNG)
Sud et al. (2007b) – USA	Adaptive roadmaps

Table 2.3: continued

Pelechano et al. (2007) -USA	Social and physical forces model
Hajibabai et al. (2007) - Iran	Spatial cognition

2.4 Agent based Crowd Steering Simulation Classification

This section describes the various approaches of agent-based crowd steering simulation found in the review. These approaches are shortest path, prediction, context-aware, velocity-based, density-based, knowledge-based, cooperative behaviour, leader-following, grouping, behaviour-based, obstacle avoidance, gap seeking, intelligent agent, collision avoidance, and optimisation.

2.4.1 Shortest Path Approach

The conventional approach is based on a geometric approach where the shortest path from the agent's current position to its goal position is calculated and selected. The advantage of this approach is that it is inexpensive and requires less computation time (Shendarkar et al., 2008). The Dijkstra's algorithm is the standard algorithm used to calculate the shortest path, and studies using this algorithm have been reported by Tsai et al. (2017), Patil et al. (2011), Qiu and Hu (2010), Shendarkar et al. (2008) and Van den Berg et al. (2008). Although using the shortest path could minimise computational time, it is inapplicable for a dynamic environment, where there are possibilities that some of the pre-calculated paths are inefficient to be used.

Foudil et al. (2009) designed a system focusing on collision handling for real-time pedestrian behaviour in crowds. An A-star algorithm is adopted for path planning to compute the shortest paths to the destination. A-star algorithm is applied to the

visible regions of each agent. Collision handling is performed using priority rules. The model could be used as a framework to simulate real-life situations, but it needs to be extended to include natural human interaction. This framework was initially designed to simulate individual agents. Thus, an interaction model must incorporate a group of agents.

Van Toll et al. (2015) proposed a five-level hierarchy for solving agent navigation problems in games and simulations. In their work, the agent navigation process is subdivided into sub-processes. The simulation framework is built using an Explicit Corridor Map (ECM) that consists of three components; the geometric aspect of navigation, global planning, and route following and local movement. The flexible and extensible simulation framework can simulate real-time agent navigation and collision avoidance. However, since the grid size is fixed, the simulation of highly dense crowds and groups of crowds is not promising because of the complex computation performed to evaluate each agent.

2.4.2 Prediction Approach

The prediction approach requires machine learning and a high computational process. Nowadays, advances in computer technology have increased the interest in using this approach. This approach is commonly used to predict the paths that lead to the least travel time, which is the safest and least congested path. Work has also been done on predicting future collisions by computing the time of collision.

Oliva and Vilhjálmsón (2014) designed a path-following model by predicting agents' social intentions and movement. The model also has social protocols and randomness to achieve uniqueness and realism in agent movement. The agent is

designed with social attributes that allow them to interpret territories and predict social intentions. The built model is adaptive, and all parameters will be automatically adjusted to available system resources. Despite this model's excellent performance, a detailed evaluation, such as a comparison with other approaches, is needed to study its performance.

Rösman et al. (2017) presented an online trajectory planning optimisation algorithm by employing the timed-elastic-band (TEB) approach, which had been generalised to an efficient time-optimal model predictive control approach for dynamic systems. This work is dedicated to robot planning in crowded environments where dynamic path planning is important. The robot agents could respond to environmental changes by adapting their plans. However, no straightforward communication occurs; the robot agents signal their intentions when they move to the opposite side. The agent must also be updated on the other agent's trajectories when they encounter each other. However, one assumption is made before an agent can plan its trajectory. The assumption made is that the agent must already know the trajectory of other agents they are communicating.

Vemula et al. (2017) designed an algorithm that allows robots to navigate through dense crowds. The idea in this work is to let agents cooperate with other agents to achieve their goals while avoiding collisions. The future trajectories of agents are predicted based on previous trajectories. Meanwhile, real human trajectory data was used to model the local interaction for collision avoidance, thus giving higher performance for collision handling. However, static obstacles are excluded from the model, which would produce slightly unreliable results for collision avoidance.

Furthermore, the model is not generic; new models are needed when a new environment is designed for the simulation. This is caused by the assumption that every goal is known in the environment.

2.4.3 Context-Aware Approach

In crowd steering simulation, a context-aware approach refers to the methodology or technique used to simulate the movement and behaviour of crowds in different circumstances, taking into account significant environmental and situational elements. The objective of crowd steering simulations is to simulate the navigation behaviour of people inside a crowd to avoid collisions, congestion, and various impediments.

The context-aware agent perceives the changes in parameters (e.g., crowd agent density, neighbouring agents' velocities) in the environment. An agent frequently updates its knowledge about the environment by requesting the recently updated information from the knowledge database. This approach is most suitable for dynamic path planning, whereby the initial computed paths are no longer available due to unexpected events such as congestion.

2.4.4 Velocity-Based Approach

The crowd steering simulation employs a velocity-based methodology that centres on representing individual movement within a crowd, taking into account their respective velocities and directions. This methodology involves representing each member inside the crowd as a point entity accompanied by a distinct velocity vector that signifies their present speed and direction of motion.

Lin et al. (2008) extended the Reciprocal Velocity Obstacle approach to solve the challenging problem of handling multiple agents in an environment with static and dynamic obstacles. The solution is derived based on two assumptions; 1- each agent has a high-level cognitive map of the environment, and 2- each agent can make a decision and re-planning by choosing the suitable velocity according to other agents' velocity. The global path is extracted from the roadmap generated during the pre-processing phase. The approach has some advantages, such as the automatic lane formation, the natural look of agents' flow in crowded scenes, and agents not repelling each other. One limitation of this approach is that the reciprocal dance phenomenon that emerged when two agents were positioned in opposite directions took some time before they could pass each other.

Xiong et al. (2009) proposed rule-based motion planning by categorising agents into three types consisting of agent preferences to realise the real pedestrian behaviour in real life. The valid velocities chosen by agents was sampled and evaluated using expected time to collision. However, some conditions need to be followed for the chosen velocities. The expected time to collision for that velocity must be larger than the threshold velocity, and the chosen velocity is the first velocity that satisfies the conditions during sampling. However, collision will occur between agents when agents have no other option but to choose the velocity with the largest expected time to collision.

Van den Berg et al. (2011) designed an approach for collision avoidance known as acceleration-velocity obstacles. This approach allows a robot agent to avoid collisions with moving obstacles while observing the acceleration constraints. Experiments show that robot agents achieve convincing, smooth, and collision-free

motions while maintaining the acceleration constraints. However, this model assumes that the robot agent uses the same strategy for collision avoidance, acts independently, and can perceive the physical properties of other robots.

Godoy et al. (2016a) proposed a Coordinated Navigation (C-Nav), a distributed approach to improve the global motion of agents in crowded environments by implicitly coordinating their local motions. Agents are designed to be able to choose their preferred velocities, thus improving the motion performance of the entire crowd. Moreover, this approach is designed for large-size multi-agent systems. However, for the agents to decide on their preferred velocities, they need to rely on the velocities of neighbouring agents. Thus, the assumption is made that all agents can share publicly their velocities with other agents.

2.4.5 Density-Based Approach

In crowd steering simulation, a density-based approach is employed to mimic a crowd's behaviour and movement patterns by considering the distribution and density of persons inside a certain area. The crowd's density in various regions is pivotal in shaping individuals' navigation and interaction with their surroundings within this specific approach.

Van Toll et al. (2012) designed a technique to distinguish desirable routes using distance and crowd density information. This approach is preferable as it can avoid congestion paths using the local density information. The environment is converted into a navigation mesh that creates a walkable region which performs frequent updates of density value. The model can perform real-time navigation for thousands of characters through a 2-D or multi-layered 3-D environment. However,

there is one limitation to this model. The walkable region generated could be different in size. Thus, regions with small sizes have higher densities compared to others. This will eventually affect the desirability of a particular route.

2.4.6 Knowledge-Based Approach

In crowd steering simulation, a knowledge-based approach integrates domain-specific knowledge, rules, and heuristics to replicate crowd behaviour effectively. This methodology depends on a pre-established understanding of human behaviour, societal rules, environmental limitations, and other relevant factors to direct the motion and engagements of persons within a crowd.

Sud et al. (2007b) simultaneously performed dynamic global path planning for independent agents using Adaptive Elastic Roadmaps (AERO). AERO is a path-planning data structure that can perform immediate updates in response to agents' motions and obstacles. They also modelled agents' behaviour to translate motion into animated characters using pre-determined behaviours; stop, walk and jog. Their algorithm can simulate individual agents in real-time including high performance for collision avoidance. However, their simulation produced no realistic motion due to the high number of agents and was not generic. There will be different simulation results for different environments.

Sud et al. (2007a) constructed a Multi-agent Navigation Graph (MaNG) for real-time path planning. The first and second-order Voronoi graphs are combined to construct MaNG, which is used for global path planning for multiple agents. This approach could simulate a large number of individual agents with different goals. However, it is not suitable for agents that can perform turning to any degree.

Hajibabai et al. (2007) designed cognitive agents to interpret landmarks for pathfinding during fire building evacuation. The results concluded that evacuation time could be reduced by better placement of cues. Furthermore, good signage planning, including its quality and quantity, produced the least evacuation time. However, they need to design a solution to handle the possibility of agents revisiting the point with higher knowledge.

Shi et al. (2009) designed a simulation model that consists of physical and mathematical models to simulate evacuation in large public buildings. Agents are designed to be able to re-plan strategies and make decisions based on the local environment. This simulation model is useful for evaluating the efficiency of evacuation strategies and determining the fire safety of building structures. However, this model was used to simulate the evacuation using some factors as parameters that were not fully understood in how they relate to each other. Further extensive experiments are required to verify this model.

Chen and Feng (2009) designed a fast flow control algorithm that considers the detailed parameters of the floor plan and the total number of evacuees when calculating evacuation paths. The floor plan is divided into regions in which evacuees are located. The location of each region is mapped to its corresponding node on the path network. The generated evacuation paths are based on minimum total evacuation time and an optimal number of evacuees assigned to each evacuation path. However, this approach does not consider local motion, which could influence the total evacuation time.

Ondrej et al. (2010) proposed a vision-based collision avoidance model for interactive simulation of crowds of individual humans. This approach is based on cognitive science work on human locomotion, which inspired the design of novel local visual-stimuli or motor-response laws. The result demonstrated the ability of this approach to address complex interaction situations between numerous walkers. Despite the realism of the simulation result achieved, a quantitative measurement should be conducted to evaluate the result properly.

Schuerman et al. (2010) presented an approach for augmenting steering framework with externalised hierarchical steering logic. In this work, a new agent called a situation agent is designed to separate the class of agents. The logic of situation agents is separated from standard agents, which reduces the complexity of standard agents. The situation agent influences other standard agents to modify their preferred velocities to prevent deadlocks, move in groups and construct a formation agent. However, the situation agent can modify only two parameters; boldness and preferred velocity.

Hu et al. (2013) developed a pattern-based steering model using spatial-temporal patterns. Their work was inspired by neurobiological and cognitive studies that concluded that the human brain can organise and categorize information by using patterns. This simulation model allows agents to choose the most appropriate steering strategies according to the situation. The simulation result indicated that agent crowd density has some effects on this model where high density has a greater impact on the agent's decision on steering strategies. Moreover, for complex scenarios, patterns are difficult to perceive.

Liu et al. (2018) proposed a knowledge-based crowd evacuation approach that uses navigation knowledge and a two-layer control mechanism. The population is divided into groups, and each group is assigned a leader who is selected according to fitness value. Another agent, called the navigation agent, will collaborate with the leader agent to direct the other agent to the destination. The proposed approach could resolve the slow speed problem that is effective for problems related to microscopic models. However, the simulation scene used was simple and, thus, did not result in a good performance for larger crowds.

Wu et al. (2018) developed an information attraction model by integrating a voice warning system and a crowd simulation system in large indoor spaces. The simulation model was developed based on cellular automata by extending existing cellular automata model. Their experimental result shows that environmental conditions vary in the evacuation process. Although in most experiments, evacuees tend to choose the same exit route, their velocities vary through different sections of the environment. They concluded that elements of exit routes, their visibility and voice warning system have significant influences on the average velocities of evacuees.

2.4.7 Cooperative Behaviour / Social Interaction with Communication Approach

The crowd steering simulation utilises the social interaction with communication approach to incorporate social interaction and communication mechanisms among individuals in a crowd, resulting in a more accurate and subtle representation of behaviours. In contrast to alternative methodologies that primarily concentrate on physical elements or predetermined regulations, the SIC approach

places significant emphasis on the impact of social dynamics, encompassing both verbal and non-verbal forms of communication, on the behaviour of crowds.

Interaction between agents describes the agents' motion, which is influenced by neighbouring agents and obstacles (Dutra et al., 2016). Compared to commonly used approaches such as the shortest path and prediction method, social interaction and communication have a number of advantages, including increasing simulation realism and producing emergence behaviour. It is also suitable for a mobile context during evacuation simulation.

Viswanathan and Lees (2011) designed additional modules for motion planning algorithms, group sensing and perception filtering. The idea is to group all the perceived information by each agent inside a knowledge database before performing sensing and filtering. A filtering process is conducted to make sure that the information is limited only to the most important to the agent by choosing the one with the highest score. Although the simulation result indicated that group avoidance behaviour is seen to be realistic, this approach reduced the efficiency of collision avoidance since the perception of each agent is limited.

Duives and Mahmassani (2012) proposed a discrete choice model using multinomial logit model (MNL) to represent pedestrian exit choice decisions during evacuation. They conducted a survey to obtain significant choices that respondents selected. The survey indicated that the following behaviour has a significant influence on exit selection to find the nearest exit. The simulation model built was based on the decision made by respondents during the survey. However, the model does not consider some important parameters for evacuation such as variations of agents'

velocities at the exit door, variations of agents' profile (i.e., location, direction and speed) and self-organisation which is important for realism in local motion.

Rojas et al. (2013) developed a group agent-based steering to solve realistic corner turning by assigning slots to each group. Slots are designed to group agents close to each other and this approach is adaptive to the floor space (i.e., width). However, the fixed number of slots assigned to each group (five slots) could cause chaotic events when there are many agents situated inside the environments. Performance of simulation also may reduce due to high number of groups in simulation model that consists of large number of agents.

2.4.8 Leader-Following Approach

In crowd steering simulation, the leader-following approach is simulating the movement of individuals in a crowd by assigning specific agents as leaders and permitting other agents to follow their paths. This methodology is derived from empirical studies of how individuals in large gatherings tend to synchronise their actions with those they view as authoritative or influential. Pelechano et al. (2007) proposed a leadership model for building evacuation by using mental map. As agent explores the building through navigation, mental map is updated by adding the new nodes to the portal graph. This study is conducted to examine the optimal number of leaders that suitable for the best evacuation rates. The simulation results show that only a relatively small percentage of trained leaders produce the best evacuation rates. However, agents' individualistic is not implemented, thus it lacks realism.

Hou et al. (2014) design an evacuation model by extending the Social Force Model. They designed some agents to be trained leaders that having the information

of location of exit doors. The untrained agents are designed to follow the instructions only from trained leaders. The authors concluded that the position of leaders is significant compared to the high number of trained leaders. In other words, a high number of trained leaders will not confirm the optimum evacuation rates. Thus, for single exit experiment setup, a maximum of three leaders would be optimum. However, this simulation only examines the effect of leaders' position in the environment, thus the position and spreading of fire in the building are not considered. Hence, the model could not be implemented in dynamic environment.

Fang et al. (2016) designed a leader-follower model to understand local social interaction and collective behaviours during evacuation. Agents are designed to construct informal and temporary relationship with between them by becoming a leader or a follower. However, the model only simulates three scenarios; lining up, queuing and collective mobility and more experiments are needed to study its capability for evacuation scenario.

Juniastuti et al. (2016) adopted Reciprocal Velocity Obstacles (RVO) to create oscillation and collision-free motion in multi-agent navigation by combining RVO and leader-following behaviour. In this work, follower agents are designed to navigate by following the leader to the destination. The result shows that the use of leader-follower relationships in crossroad scenarios and narrow passage scenarios produced reduced time for agents to navigate to their destinations. However, in both scenarios, only 200 agents maximum are tested. Moreover, the time taken for any agent to change its current velocity depends on the current simulation cycle. This is because the follower agent is designed to follow the leader agent, which makes the movement of the follower agent constrained by the leader agent.

2.4.9 Grouping Approach

In crowd steering simulation, the grouping approach simulates crowd behaviour by categorising individuals into several groups or clusters according to different factors, such as spatial closeness, social connections, or shared goals. This technique recognises the inclination of individuals inside crowds to establish groups or clusters and takes into account the impact of group dynamics on the overall movement of the crowd. Grouping behaviour represents the phenomenon through which some individual agents prefer to stay close to each other and move in a group.

Qiu and Hu (2010) modelled the group structure of a pedestrian crowd from two aspects; intra-group structure and inter-group relationship. Each agent is designed to have a speed vector for obstacle avoidance and random movement and another two-speed vectors for maintaining group behaviours. However, few assumptions have been made. First, a predefined group structure is used through the simulation. Second, leader agents are pre-selected and not replaceable. In other words, this simulation model does not consider the design of the group structure to be dynamically changed.

2.4.10 Behaviour-Based Approach

A behaviour-based approach is commonly employed to design a more realistic crowd agent simulation close to real human behaviour. Shendarkar et al. (2008) proposed a novel crowd simulation development methodology, where the BDI agents driven by the human behaviour data extracted from the virtual reality (VR) experiments are used to build a crowd simulation. The crowd simulation has been applied to study evacuation situation in the event of a terror attack at the National Mall area in Washington DC. Experiments were conducted to explore evacuation scenarios

under various environmental conditions. However, this model requires high computation speed.

Tsai et al. (2018) applied Dijkstra's algorithm with the visibility graph to construct the navigation field but excluded parameters such as agent's size, agent's density and agent movement speed. The proposed approach will generate a guidance path around the corner regions whenever congestion occurs at corner region. Crowd monitors are placed at corners to compute crowd density and retrieve movement directions. Moreover, a scheme is introduced to speed up the process of collision detection. However, this model is not designed to handle moving obstacles (i.e., moving agents). Thus, the guidance paths may not be the best solution to solve intersecting agents.

2.4.11 Obstacle Avoidance Approach

The primary objective of the obstacle avoidance approach for crowd steering simulation is to simulate the way in which individuals within a crowd navigate around obstacles or barriers present in their surroundings. This strategy is essential for accurately replicating crowd behaviour in situations where there are tangible barriers that individuals need to overcome.

Narain et al. (2010) designed a simulation model for local motion planning by capturing the discrete motion of each agent and the discrete flow of the crowd. This model could simulate large crowds that are up to 100 thousand agents and could be used with any global planner model. However, this model limits the behaviour of crowds to simplify the mathematical formula. Another limitation is that agents can

only access local information to avoid collisions. Thus, they can react to potential collisions when they are at a close distance.

2.4.12 Gap Seeking Approach

In crowd steering simulation, the gap-seeking approach is used to simulate how individuals in a crowd navigate by actively searching for and moving towards gaps or openings in their surroundings. This approach is especially relevant in situations where persons are required to traverse through densely populated environments with restricted resources or congested areas.

Luo et al. (2017) introduced a proactive steering strategy to add realism to crowd simulation. The model is a behaviour-based model for gap-seeking and following behaviours. Triggering condition is defined for each proactive steering behaviour to trigger the steering strategy. The model adds realism to simulation result. However, to be able to perform gap seeking, triggering condition is probabilistically depends on the agent motion towards its final destination.

2.4.13 Intelligent Agent / Learning Approach

The most recent works focus on designing steering algorithms for robotics, which benefits smart technologies such as the Internet of Things (IoT). Ozcan et al. (2019) designed a simulation model using timed-based density information and the flow direction of a crowd. This model uses machine learning methods to compute the optimum global path plan. For evaluation, they compared the proposed method to the most recent one, the Potential-based method (PBM). As a result, the conventional circle and cross scenario show that their simulation model slightly outperforms the

PBM, while for the corridor scenario, the model is better at computing a realistic global path than PBM, given that time is considered. However, the agent is designed such that each of them can access the global path plan information of other agents situated in the simulation. Thus, the agents could possibly create unrealistic behaviour when they react towards agents invisible to them.

Aroor et al. (2018) proposed two online learning algorithms for robotics that are able to learn cost maps by using local observations throughout navigation in the crowd. The CUSUM-A* algorithm is used to generate crowd-sensitive paths by computing the average number of people located in each grid cell. Meanwhile, the Risk-A* algorithm is designed to respond to human-robot interaction by using cost maps that contain the risk level of each cell. The algorithms incorporated robot interaction effects to learn accurate cost maps for global navigation. The simulation model acquires online learning; thus, training is not required for new indoor environments. Despite the constant runtime complexity of this model, it requires global knowledge for navigation, which eventually increases computation costs when involving a huge crowd.

Kala (2018) built a density-based simulation model for robot navigation in dense environments. The model is built using a deliberative probabilistic roadmap-based planning, an active re-panning, a reactive navigation system, a density conscious routing system and a deadlock avoidance system. The results indicated that robots were navigating using similar trajectories as humans. However, the model is suitable for robotics, thus some human behaviours are not included.

2.4.14 Collision Avoidance Approach

In crowd steering simulation, the collision avoidance approach aims to simulate how individuals in a crowd move while actively avoiding collisions with other individuals and obstacles in their surroundings. The utilization of this approach is important in order to replicate authentic crowd dynamics and guarantee the security and effectiveness of crowd mobility across diverse situations.

Patil et al. (2011) created navigation fields to control the crowd navigation by using user-specific guidance fields or motion flow extracted from crowd video. The result shows that this model able to compute real-time navigation fields in complex environment. Despite the high performance of this interactive algorithm, it seems impossible to create some behaviours related to humans such as social interaction.

Niu et al. (2015) proposed a model of dynamic decision-making for crowd simulation by combining local and global technology to simulate the behaviours of crowds. In this model, collision is handled using Optimal Reciprocal Collision Avoidance (ORCA). Knowledgeable agents are designed to have a willingness to share the exit information with novice agents. The increase in willingness level will result in better evacuation speed. However, there is no significant evidence of the optimum number of knowledgeable agents required to achieve optimum evacuation time.

Dutra et al. (2016) designed a gradient-based algorithm that is able to steer agents by minimising the risk of collision. A cost function is introduced to evaluate visual information at each time step. The agent is designed to adapt its motion according to the gradient value while minimising the cost function. Despite the agents

individually avoiding collision, they may also suddenly navigate off the origin path. This approach can be integrated with global motion planners to solve complex navigation.

Weiss et al. (2017) adopted position-based dynamics (PBD) to simulate virtual characters useful for interactive games. This simulation model could handle collisions in low and high-density crowds' environments. It could generate emergent behaviour and flexibility, but it is not intended for simulating real pedestrians.

2.4.15 Optimisation Approach

In crowd steering simulation, the optimisation approach involves using mathematical optimisation tools to ascertain the optimal pathways and behaviours for individuals present in a crowd. This technique's primary objective is to optimise multiple goals, including minimising trip time, reducing congestion, maximizing throughput, and ensuring safety.

Guy et al. (2010) developed PLEdestrians, a pedestrian simulation model built based on the optimisation method using the least effort function. In this model, the agent searches for a trajectory that minimises the energy consumption from its current position to the destination. In addition, agents navigate through the environment using permissible velocities that are calculated as an estimation of the minimum energy used. The simulation results show that the computed trajectories are smooth compared to other methods, such as social forces. Other than that, this model is also able to reproduce emergent phenomena such as jamming, overtaking and lane formation. Despite the good performance of this model, the motion generated by each agent is

limited such that it is based on studies of humans walking in straight lines using normal velocity. Thus, this model could not simulate panic behaviour during emergencies.

Zhong et al. (2015) designed a simulation model based on a segmentation strategy to solve evacuation planning problems. The segmentation strategy divides the environment into sub-regions consisting of an exit gate using a discriminant function. The discriminant function is optimised using the proposed evolutionary algorithm to reduce total evacuation time. This model could reduce evacuation time. However, the simulation setup is designed as an ideal condition where agents were evenly distributed across regions. Moreover, this model used only one discriminant function to handle all agents' behaviours, thus could affect the flexibility of the model and its result.

Table 2.4 summarise the agent-based steering approaches based on the state-of-the-art crowd steering models. We summarise the review according to six categories and 17 sub-categories as shown in Table 2.4. The six main categories are context-aware (four sub-categories), local path planning (two sub-categories), global path planning (three sub-categories), robotics and algorithms (seven sub-categories). It can be seen that latest steering approaches appear to use contextual information such as time, location, velocity and density.

A total of 33 out of 44 studies features context-aware ability in their steering model. The most common contextual information are velocities of other nearby agents (24 studies), while 22 studies used positions of other agents. Another 14 studies used agents' density as the context while 8 studies used time as the contextual information in their steering model. For local path planning, a total of 31 studies

reported to included collision handling in their steering model. Out of 31 studies, 10 studies modelled collision handling as real-time. A total of 13 studies did not modelled collision handling as they modelled steering as local motion which based on social or path following. There are 9 studies modelled real-time global path planning, while 21 studies modelled steering algorithm as offline path planning. A total of 14 studies did not modelled global path planning as they focused on local path planning. There are 5 studies were using pre-computed path for global path planning, while 3 studies predict path in their algorithm.

Table 2.4: The Findings: Overview of Agent-based Steering Approaches

Author / Country	Approach	Context-aware				Local Path Planning		Global Path Planning				Robotics	Mobile context	Algorithms						
		TM	DE	AP	AV	RC	CH	RP	OP	PC	PP			DJ	D*	A*	RV	MD	LG	NW
Ozcan et al. (2018) – Turkey	Time-based density information	✓	✓	✓	✓		✓		✓		✓						✓	✓		
Aroor et al. (2018) – USA	Bayesian online-learning	✓	✓	✓	✓		✓					✓				✓				✓
Liu et al. (2018) – China	Knowledge-based	✓		✓				✓												✓
Kala (2018) – India	Probabilistic roadmap	✓	✓	✓	✓		✓		✓										✓	
Rösmann et al. (2017) - Germany	Timed elastic bands					✓	✓													✓
Tsai et al. (2017) – Taiwan	Guidance path						✓													
Vemula et al. (2017) – USA	Velocity modelling				✓		✓					✓		✓				✓		
Weiss et al. (2017) – USA	Position-based			✓	✓	✓	✓											✓		
Dutra et al. (2016) – Brazil	Gradient-based						✓													✓
Godoy et al. (2016a) – USA	C-Nav			✓	✓		✓													✓
Godoy et al. (2016b) – USA	Bayesian Inference			✓	✓		✓					✓								✓
Fang et al. (2016) – USA	Scalar field method							✓	✓											✓
Juniastuti et al. (2016) - Indonesia	Reciprocal Velocity Obstacles			✓	✓		✓		✓							✓				✓
Kremyazas et al. (2016) - Netherlands	Extended Social Groups and Navigation (SGN)			✓	✓		✓		✓											✓
Luo et al. (2018) – China	Gap Seeking proactive steering						✓		✓											✓
Zhao and Winter (2016) - Australia	Fading memory model	✓				✓			✓											✓
van Toll et al. (2015) - Netherlands	Explicit corridor map			✓	✓		✓		✓							✓				
Niu et al. (2015) – China	Dynamic decision making			✓	✓		✓		✓											
Zhong et al. (2014) - Singapore	Segmentation strategy																			✓
Oliva and Vilhjálmsón (2014) - Iceland	Social intentions and movements prediction	✓		✓	✓		✓									✓				
Rojas et al. (2014) – Korea	Two-level steering			✓	✓		✓									✓				✓
Hou et al. (2014) – China	Improved Social Force Model			✓	✓				✓											✓
Hu et al. (2013) – Singapore	Patterned-based approach				✓		✓		✓											✓
Duives and Mahmassani (2012) - Netherlands	Discrete Choice Model								✓											
van Toll et al. (2012) - Netherlands	Density-aware		✓	✓	✓	✓	✓	✓	✓		✓					✓				✓
Fang et al. (2011) – China	Ant Colony								✓											✓
T and Lees (2011) - Singapore	Information-based perception model				✓		✓		✓											✓
van den Berg et al. (2011) - USA	Acceleration-velocity obstacle (AVO)			✓	✓		✓						✓							✓
Patil et al. (2011) – USA	Goal-directed navigation					✓	✓	✓						✓						✓
Ondrej et al. (2010) – France	Synthetic vision-based			✓	✓		✓													✓
Guy et al. (2010) – USA	Principle of Least Effort			✓	✓	✓	✓	✓		✓							✓			✓
Qiu and Hu (2010) – USA	Shortest Path			✓	✓		✓		✓					✓						✓
Schuerman et al. (2010) - USA	Situation Agent			✓	✓		✓		✓								✓	✓		
Naraian et al. (2010) – USA	Aggregate Dynamics						✓		✓											✓
Chen and Feng (2009) - Singapore	Fast flow control algorithm							✓												✓
Shi et al. (2009) – China	Physical System Dynamical Model																			
Foudil et al. (2009) – France	Cell decomposition			✓	✓	✓	✓		✓							✓				
Xiong et al. (2009) - Singapore	Rule-based motion planning						✓										✓			
Shendarkar et al. (2008) - USA	VR-based BDI						✓		✓	✓				✓						✓
van den Berg et al. (2008) - USA	Precomputed map			✓	✓		✓		✓	✓	✓			✓			✓			
Sud et al. (2007a) – USA	Multi-agent Navigation Graph (MaNG)		✓			✓	✓	✓												✓
Sud et al. (2007b) – USA	Adaptive roadmaps		✓			✓	✓	✓								✓				✓
Pelechano et al. (2007) -USA	Social and physical forces model						✓			✓										✓
Hajibabai et al. (2007) - Iran	Spatial cognition								✓	✓										✓
Context-aware	Local Path Planning	Global Path Planning						Algorithms						Algorithms						
TM : Time	RC : Real-time Collision Handling	RP : Real-time Path Planning						DJ : Dijkstra's algorithm						MD : Modified algorithm						
DE : Density	CH : Collision Handling	OP : Offline Path Planning						D* : D-star algorithm						LG : Learning algorithm						
AP : Other Agents' Position		PC : Pre-computed Path						A* : A-star algorithm						NW : New algorithm						
AV : Other Agents' Velocities		PP : Path Prediction						RV : Reciprocal Velocity												

Various existing algorithms have been used such as Dijkstra's algorithm, D* algorithm, A* algorithm, reciprocal velocity obstacles algorithm, learning algorithm and cultural algorithm. Many studies reported has modified the existing algorithm. A total of 26 studies developed new algorithms in their model. A total of 6 studies have been reported to model the steering algorithms that suitable for robotics. A total of 23 studies reported that their model features scalability in which it could be implemented in highly dense crowds, could be extended to enhance it features and could be easily used together with existing path planning model. Although those models are implemented, none of the works focus on simulating crowd steering in mobile evacuation scenario.

2.5 Discussion

The emerging of crowd steering studies is happened since 1987. As agent steering is a complex process considering the heterogenous of each agent, the common challenge in agent steering is to compute the complete set of collision-free paths with least travel time. During year 1987, Reynolds has introduced 25 steering behaviours for autonomous characters (e.g. agents) that unfold many research opportunities afterwards. From the review, the existing crowd steering approaches vary from each other according to its main purpose. The common approaches are based on finding the nearest exit based on shortest path, using Dijkstra's algorithm as in Rahman et al. (2008), Wu et al. (2014), Patil et al. (2011), Chen and Feng (2009), Tsai et al. (2018), Shendarkar et al. (2008), Qiu and Hu (2010), Guy et al. (2010) or using A* path finding algorithm as in Foudil et al. (2009), Kala et al. (2018), Juniastuti et al. (2016), Oliva and Hannes (2014), Rojas et al. (2014), Van Toll et al. (2012) and Sud et al. (2007b). The typical steering approaches in evacuation context are not for highly

dynamic context where the paths given to people could change over time. Paths given to people should be dynamic to adapt to surrounding situations with aim to ensure optimum safety to all people. Recent advances in computing has great advantages to perform simulation with high computing power. Latest research in steering crowds has involved some sort of prediction based on previous knowledge acquired by learning. There are studies for global path prediction and obstacles collision prediction. Ozcan et al. (2018) included prediction model for online phase to be used in global path planning process. The learning data set is trained using artificial neural network, polynomial regression and support vector machine. The model created is context-free; no parameters setup need (i.e., number of agents, initial and goal position), but the graph structure must be same for both mini-simulation and real environments. Vemula et al. (2017) predicted the future trajectories of agent from its previous trajectories. The velocities modelling is performed using Gaussian process. Oliva and Hannes (2014) designed a prediction model that predicts social intentions and movements of agents using velocity-based approach to demonstrate path following behaviour.

Most recent steering approaches regard agent as intelligent and could make decision on its own. Intelligent agent is designed as context-aware and decide on solution many times based on frequently context update. If each agent received updated information such as travel time for each available path, they can make better decision. To frequently provide such updated information would require real-time computation. Van Toll et al. (2012) presented a technique for guiding moving agents to lower crowd density route using real-time updated information. Weiss et al. (2017) updated the agents' velocities once the new positions are computed to guarantee stable

agent velocities. Liu et al. (2018) updated the historical knowledge in the knowledge base which contains path record and running time after each evacuation for dynamic path planning. However, in situation where number of people is large, the suggested paths are potential to become a threat to people. This is because the paths leading to the exit might be fully occupied or in other word, the paths are congested. Even though the paths should literally take people to exit in short time, that might not happen in the case of congestion. Congestion will lead to extra time taken to exit the building Rahman et al. (2008).

As technology is going advanced, the adoption of mobile technology in crowd evaluation is yet to be explored based on the current review. Hence, this lead to the research gap as investigated in this thesis.

In general, the agent crowd steering simulation involves studying a mechanism to navigate one or more agents from one location to another location in the same environment. There are a few characteristics of agents that are important during the steering process, such as personal space, velocity adjustment ability, context awareness, and context interpretation. Each agent should have its own personal space that cannot be invaded by other agents, either when they are moving or in static. This private personal space could prevent the agents from the potential collision of agent-to-agent or agent-to-obstacle. To maintain smooth navigation through walkable space in the environment, agents should be able to adjust their velocity according to the average velocities of nearby agents. The velocity adjustment ability is essential for the local motion of agents. To allow the agent to respond to dynamic change in the environment, the agent should be in the context-aware state. Agents should be able to

discover information that frequently changes in their surroundings, such as temperature, humidity, other agents' positions and velocities, and other information related to the building.

The agent also should have context interpretation characteristics. According to Chen and Kotz (2000), context is any available information useful for describing the situation of an entity, such as individual, type of activity, time and location. Contextual information that is relevant to agent steering consists of the agent's position, the agent's velocity and other neighbouring agents' positions and velocities. Context-aware is an agents' behaviour that frequently discovers its surroundings to update its local knowledge regarding the environment. The agent should be able to interpret the environment's context to decide on the best solution. For example, if too many people move towards the nearest exit, agents should be able to find other exits to avoid congestion based on agent crowd density information that could be accessed by the agents according to their position in a specific region.

In sum, we can summarise the important aspects of modelling agents in mobile crowdsteering systems as follows.

i) Model general parameter.

It is necessary to meticulously model the general parameters of an agent, such as their physical information (e.g., age, physical disabilities, and heart condition). It is necessary to configure it based on actual data in order for the simulation to be able to generate results that are comparable to the actual world.

ii) Model behaviour.

It is important to consider the agent's behaviour because it will help determine how they will react in various emergency situations. For instance, if there is only one exit and a crowd of people is trying to exit the door at the same time, the agent's behaviour of not pushing other people in front of them or pushing other people in front of them will determine whether or not the total evacuation is safe. Another behaviour seen during evacuations is following other people's lead. The core principle of an efficient steering algorithm is the ability to perform re-planning to generate new paths according to present contextual information. In other words, every time contextual information is updated or changed, the re-planning module will perform its action to compute new paths. Out of the categories on crowdsteering behaviour, this thesis selects the social force approach as the baseline model when simulating a mobile crowd evacuation system. The implementation of social interaction or communication between agents is essential for the purposes of emergency evacuation. The ability of each agent to interact with other agents has the potential to increase the performance of the crowd steering model as this behaviour depicts plausible real-human behaviour. The grouping and leader following a steering approach is an example of implementing social interaction among the agents. Our selection is also inspired by Pelechano et al. (2006). Pelechano et al. (2006) designed an agent as a trained leader. They created a simulation that mimics the behaviour of a trained leader during the evacuation of a building. The leader has been trained, and the following agents, who know less about the building, are guided by the leader. The findings

demonstrate that there is a considerable increase in the pace of evacuation if there is communication occurring between the agents. As guiding people to evacuation is social-centric, it is sensible to focus on social strategy in our research. Among the social interactions mentioned, the focus of this research is using the Social Force Model. The Social Force Model (SFM) has been extensively used to simulate emergency evacuations for a wide variety of situations, including subway stations (Zhang et al., 2020), stadiums (Ming et al., 2017), and earthquakes (Zhou et al., 2020; Zhang et al., 2018). SFM has also been enhanced over the years to account for the realities of building evacuation. For instance, to address the current guide situation, researchers have examined the use of SFM when there are emergency signs inside the building (Zhou et al., 2018; Yuan et al., 2017), building personnel (Ming et al., 2017), and rescuers (Tian et al., 2020). Additionally, SFM has been used to examine the effect of leadership during evacuations (Hou et al., 2014). SFM is well suited for crowd evacuation scenarios involving both low and high crowd densities. To lower the computational cost for modelling and simulating crowd evacuation involving large-scale settings, the grouping technique is widely adopted. Grouping techniques in SFM involve the calculation of forces for each group. Rather than calculating the force for everyone, they calculated the forces for each group. When there is a group formed, a leader is then assigned to the group (Du et al., 2018). The leader's primary role is as a navigation guide to its group members. The position of leader during the navigation within its group normally positioned at the centre of the group (Zhang et al., 2018). When there are multiple groups within the simulation, they have chances to collide

with each other. To solve this issue, Huang et al. (2018) introduced group avoidance within different social groups. In their work, the group member able to adjust the group structures to control the anticipation distance from another closer group. The smooth adjustment avoids the group collision to occur. SFM has also been enhanced to realise the effect of grouping techniques by introducing the human guide (leader) into the formulation. Grouping is a technique that is widely used to reduce the cost of processing. The performance of the computation is improved since the grouping technique treats a group of agents as if they were a single agent. In order to carry out grouping approaches, a single feature from each of the agents must be taken into consideration in the formulation. For instance, Liu et al. (2018) decide who is a member of the group based on the social relationships between the participants. In the work, distinct value is assigned to each type of people such as friends, colleagues, and family, then people with close value of social relationship will be grouped together. This is close to real-world situations in which people tend to move along with their close social partner. The process of choosing a leader from a group of pedestrians varies. For example, in the work of Zhang et al. (2018), any pedestrian that is positioned at the centre of a group will be selected as a leader. In another study, the leader is pre-defined during the initialisation of the simulation environment (Hou et al., 2014; Liu et al., 2018). In the work of Hou et al. (2014), the pedestrians are divided into two types: trained leaders and normal pedestrians. Trained leaders have the knowledge of which exit they should use to evacuate, while normal pedestrians follow the destination and position of the leader.

iii) Model knowledge.

The agent-based crowd steering model relies heavily on knowledge to function correctly. In order for an agent to be able to respond appropriately to certain types of emergencies, that agent must possess some knowledge. For instance, if the hallway were to catch fire, which other hallways could the agent use to get out of the building? The knowledge they have of the building plan they have in mind will be considered when making the decision.

iv) Model environment and context.

To allow interaction with other agents, aspects of the environment, such as the building structure and its properties, must be modelled. One example would be designing the number of exit doors and their position and size. The environment also includes fire. When simulating a realistic situation during an emergency, the rate at which a fire spreads should be modelled. These aspects can serve as the design principals in designing a simulation model for mobile crowd steering, as stated in Chapter 3.

2.6 Chapter Summary

This chapter discusses the mobile crowd evacuation system, a crucial disaster prevention and mitigation component. It emphasizes the importance of crowdsourcing systems in emergency evacuations, particularly in time-critical situations. The use of smartphones and smart wearable devices has led to the development of applications that allow evacuees to quickly locate themselves inside a building and receive straightforward evacuation instructions. Several mobile applications have been introduced to assist people in evacuating open spaces or indoor spaces during emergencies, providing personalised evacuation instructions.

Agent-based crowd steering is an emerging research area, as handling the crowd during emergencies can be challenging due to unpredictable panic behaviour. Crowd steering simulation is a method that uses domain-specific knowledge, rules, and heuristics to replicate crowd behaviour. It relies on understanding human behaviour, societal rules, environmental limitations, and other factors to direct the motion and engagement of persons within a crowd. Several studies have proposed methods for simulating crowd movement, including motion planning algorithms, group sensing, and perception filtering. However, these methods often lack consideration of important parameters for evacuation, such as agent velocities, profile variations, and self-organisation.

The leader-following approach in crowd steering simulation simulates individuals' movements by assigning specific agents as leaders and allowing others to follow their paths. Several models have been developed to simulate various scenarios, but more experiments are needed to study their capability in dynamic environments.

Various approaches have been proposed to simulate agent-based crowd behaviour, including grouping, behaviour-based, obstacle avoidance, gap-seeking, and intelligent agent/learning approaches. Collision avoidance, dynamic decision-making models, gradient-based algorithms, position-based dynamics, and optimisation approaches have ensured security and effectiveness in diverse situations. Navigation fields, dynamic decision-making models, gradient-based algorithms, position-based dynamics, and optimisation approaches have been used to simulate crowd dynamics and ensure security and effectiveness in diverse situations. Although

the models are developed, there are insufficiency to work on the mobile crowd simulation context. Hence, it is worth to research.

CHAPTER 3

A SIMULATION EVACUATION MODEL

3.1 Research methodology

The research in this thesis used the Design Science Research Process model (DSRP) suggested by Peffers et al. (2007) to address the research questions. The DSRP Model is widely employed in information systems and computer science research. It is a guiding framework for creating and assessing novel artefacts, including systems, algorithms, and approaches. The framework offers a systematic methodology for researching to generate novel solutions to real-world issues. The Design Science Research Process (DSRP) model often has multiple iterative phases, each dedicated to addressing certain facets of the design and evaluation process. This thesis utilises the following methodologies:

- i. Problem identification and motivation.

One primary concern associated with the current mobile crowd steering system is resource utilisation. How can the efficacy of a mobile crowd steering system be assessed in real-life scenarios that closely resemble controlled environments? The mobile crowd steering system that is currently in place has undergone testing within a controlled setting. Therefore, the findings do not apply to unforeseen circumstances, such as disrupting a building's communication network.

ii. Objectives of a solution.

This study aims to propose an agent-based simulation model for mobile crowd steering that can be expanded to accommodate real-world scenarios.

iii. Design and development.

During this phase, a thorough examination of the current agent-based mobile crowd steering methodologies is undertaken. As determined by the study, an agent crowd steering model is developed to provide mobile crowd steering during evacuation. In this research, NetLogo is used as our simulation tool to develop the simulation model. NetLogo is a powerful programming language and modelling environment utilised for simulating complex structures featuring multiple agents. It has significant popularity in the domains of agent-based modelling, computational social science, and artificial life. NetLogo, a platform created by Uri Wilensky at the Centre for Connected Learning and Computer-Based Modelling at Northwestern University, offers a user-friendly interface for creating, exploring, and analysing agent-based models pertaining to dynamic systems.

iv. Demonstration.

To validate the proposed model, several evaluation mechanisms are introduced. Once can develop the evacuation model using virtual reality and capture real user evacuation behaviour during the virtual reality experiment. For example, Liu et al. (2024) proposed an

improved model for guided fire evacuation through guided cellular automata. Then, a virtual reality experiment is conducted to study two types of scenarios; guided, unguided evacuation. On the other hand, the simulation results can be compared with data collect from the user survey. The survey collects statistical data on the psychological and behavioural characteristic of pedestrians during emergencies Zhang et al. (2025). This thesis takes the third approach as in Nguyen et al. (2022) in which a simulator of mobile crowd evacuation system is implemented a simulator to show how the proposed system works and compare the simulation results with a famous baseline approach, Social Force Model crowd steering model. In this thesis, the Social Force Model is utilised to evaluate the efficacy of our agent crowd steering simulation model design. The evaluation and demonstration of simulation model findings are conducted by employing the original Social Force Model, an updated version of the Social Force Model incorporating the agent messaging model, and the leader-follower model.

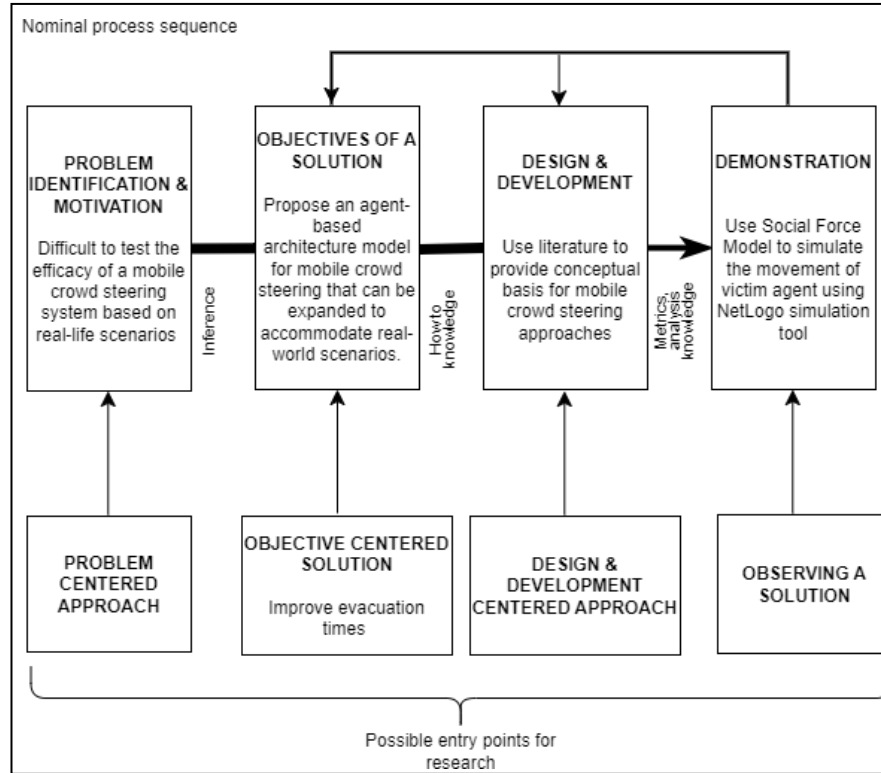


Figure 3.1: Design Science Research Process (DSRP) Model

3.2 The Design Principle of Agent Simulation Model

A simulation model for mobile crowd steering is presented in this section. In this section, the workflow of a mobile crowd steering system is presented. This is followed by the elaboration on design criteria for the agent crowd steering simulation model. The purpose of this model is to simulate a practical mobile guidance system that closely resembles existing systems, as demonstrated in previous studies conducted by Chen and Liu(2018), Itoi et al. (2017), and Zualkernan et al. (2019).

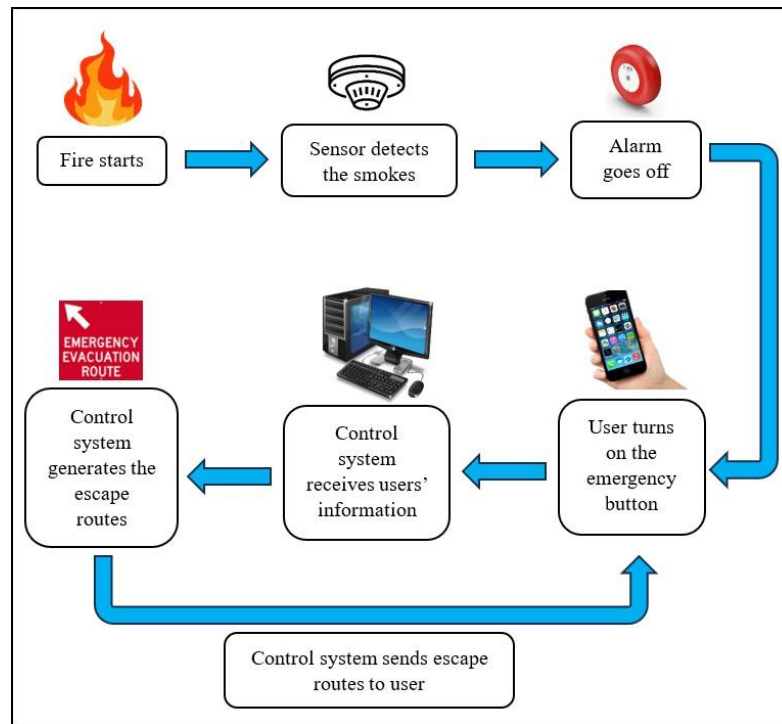


Figure 3.2: Workflow of Mobile Crowd Steering

The workflow of the mobile crowd evacuation system is shown in Figure 3.2. In the mobile crowd steering, users will receive guidance towards the exits. When the alarm goes on during an emergency, the control system will warn the victim by sending the notification to their mobile phones (Chu & Wu, 2011). The early notifications received will allow the victims to respond appropriately. It is vital for the mobile guidance application to have access to people's locations and convey that information to the central system where the processing takes place. The people's location can be detected from the smartphone or automatically determined through beacons (Zualkernan et al., 2019) and RFID readers (Jiang, 2019). The accurate location of individuals determines the best routes of escape that people need to take to

evacuate the building successfully. The route was generated by determining the shortest route possible while also considering the fire's location.

Table 3.1: The Proposed Design Criteria For The Agent Crowd Steering Simulation Model

Criteria	Model parameter
Contextual information	Social setting and social structure
Demographic factors	Person/Agent role (leader, follower)
Recipients' tendency to handle messages	Willingness (to follow the crowd, to avoid congestion, and to avoid unknown egress routes alone)
Mobile network communication channels	Assume the mobile network is reliable
Information dissemination mode	Message propagation or direct communication
Message type	Assume it is text or voice messages

Table 3.1 shows the design principle for the agent simulation model. The design principle is based on the existing survey to understand how humans make evacuation decisions upon receiving guidance to evacuate.

A survey is conducted among underground miners on the effect of text message alerts on miners' evacuation decisions (Ur Rehman et al., 2020). According to (Ur Rehman et al., 2020), a message should provide detailed information like hazard, location, guidance, time, source, and demographic factors of the victims. In addition, the quality of the message (Jayawardene et al., 2021) should cover

dimensions like clarity, certainty, consistency, accuracy, and sufficiency of the message. There are issues like recipients' tendency to ignore messages (Zhu et al., 2020), the use of synchronous and asynchronous channels to spread the messages, multiple redundant messages and types of messages like voice vs text communication messages (Ur Rehman et al., 2020). On the other hand, the details of the message are also highlighted as one of the important factors for people to follow a route recommendation in mobile application based on the online survey among football fans students and faculty associates (Mayr et al., 2023).

The effect of social influence is conducted by Mayr (Mayr et al., 2023; Fu et al., 2021) in the study of social identity and grouping in mobile guidance evacuation systems. Online surveys are conducted (Mayr et al., 2023) among football fans, students, and faculty colleagues. It is interesting to report that people follow mobile guidance due to social identity in which group or team spirit is one of the factors. An experiment is conducted among 42 participants from the University of Florida to study the people following behaviour during evacuations through an immersive virtual reality experimental study (Fu et al., 2021). The results show that individual evacuation decisions are influenced by detailed environmental information and neighbours' decisions. On the other hand, experiments are conducted among different group settings to compare the evacuation decision of isolated individuals vs individuals in small groups. The results show that group size has influenced the evacuation decision (Cuesta et al., 2021).

Mayr (Mayr et al., 2021) analysed information dissemination in guiding pedestrians in safety-relevant situations through direction communication in a moving

crowd. They discovered that direct communication is useful in redirecting crowds to a safe situation. Zhu (Zhu et al., 2020) surveyed the factors that influence people to follow evacuation signs during building evacuation among 500 participants. From the findings, neighbours or surrounding pedestrians have influenced the evacuation decision.

According to the survey, clarification of the message is important in evacuation decisions, and the channel of communication does not significantly affect evacuation decisions. In our proposed simulation model, we represent message clarification with contextual information and assume that the mobile network is reliable. Meanwhile, we represent the information dissemination mode through message propagation in which each agent will receive the information directly. In addition, crowd steering is influenced by neighbours, in which leader-follower plays an important role in mobile crowd steering. Also, group evacuation mode is important in mobile crowd evacuation. In this case, social influence will determine the willingness of people to follow their neighbour during evacuation. Finally, we assume that the quality of the message is accurate, complete, and always available.

3.3 Agent Simulation Model

From the design principle, the proposed agent simulation model consists of four modules, as shown in Figure 3.3. There are four modules involved in mobile crowd steering simulation, namely context manager, path planning, role selection, and movement. The context manager module gathers the environment profiles, such as the list of routes, list of exit doors and number of victims. Hence, the input for this module is a state of alarm (either on or off) and the state of the building (either normal or

emergency). The context manager module then passes the outputs to the next module, which is the path planning module. The outputs are a list of coordinates for fire, victims, and exit doors, the number of victims inside the building, and the number of building personnel. The path planning module determines the shortest path for evacuation based on the coordinates of exit doors and victims. The output for this module is the list of exit doors. Next, the role selection module distinguishes the role of a victim as a leader or a follower. Finally, the movement module handles the local motion of the victim by using position, desired velocity, and victims' headings as inputs.

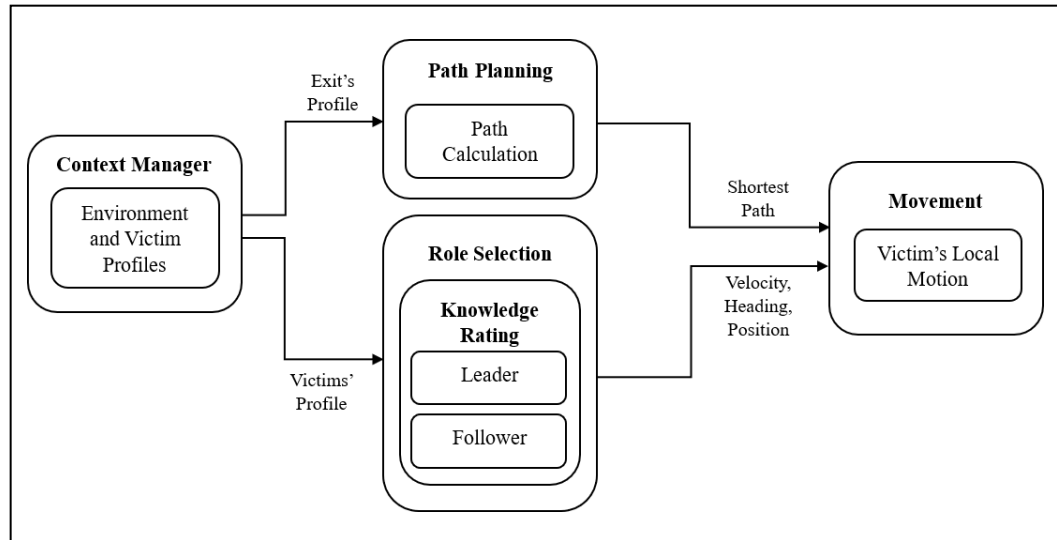


Figure 3.3: The Overview of Mobile Crowd Steering Model

Table 3.2 presents an overview of the process, input, and output for each module. Each module can be further elaborated on in the following subsections.

Table 3.2: The Process, Input, And Output for Mobile Crowd Steering Module

Module	Module Description	Input	Output
Context Manager	Gather the simulation environment profiles, such as the list of routes, list of exits and number of victims	- State of alarm (on or off) - State of the building (normal or emergency)	- List of coordinates for fire, people, and exit door - Number of people within the simulation environment - Number of building personnel
Path Planning	Determine the shortest path for evacuation	- Coordinates all exit doors - Coordinates of all people	- List of exit doors
Role Selection	Distinguish the role of a victim as a leader or follower	- Type of victim (visitor or building personnel) - knowledge level	- Role of agent (changing of the role to Leader or Follower)
Movement	Handles the local motion of the victim	- Position of victim - Desired velocity - Heading	- Victim's next walking step (XY-coordinate)

3.3.1 Context Manager Module

The context manager module acts as a central system and gathers the input from the sensor or receives the input from the victims through mobile phones. The inputs are the state of the alarm, either on or off and the state of the building, either in normal mode or emergency mode. Other inputs are the location of the victim inside the building and the location of the fire. The outputs are then sent to the next module; the path planning contains the list of coordinates for each exit node, victim, and location of fire or blocked route.

3.3.2 Path Planning Module

The path planning module acts as a path generator, which provides the path to the nearest exit door. The calculation involved is based on the shortest path to the exit door. Thus, the victims will receive the path information that leads to the nearest exit door.

3.3.3 Role Selection Module

The role selection module distinguishes the role of a victim, either as a leader or a follower. There are types of victims namely building personnel, frequent visitors, and rare visitors. Each type of victim has distinguished behaviours that are categorised as familiarity with building layout, the possibility to become a leader and pre-assigned knowledge value.

Table 3.3: Behaviour of Building Personnel, Frequent Visitor, And Rare Visitor

Type of victim agent	Behaviour		
	Familiarity with building layout	Possibility to become a leader	Pre-assigned knowledge value
Building personnel	YES	YES	1.0
Frequent visitor	YES	YES	0.5
Rare visitor	NO	NO	0

Table 3.3 shows the behaviour of each victim. A building personnel serves as a leader to the follower that are closest to him or her, then directing the follower to the exit door. This behaviour is defined by the value of the agents' knowledge.

A frequent visitor is a victim agent with an equal or greater knowledge value than one and has the option of becoming a follower of any leader within his vision or of becoming an independent victim. Because the independent victim is familiar with the building's layout, he can easily evacuate the building without following a leader. On the other hand, a frequent visitor has the option of becoming a follower or a leader. This is because this victim possesses sufficient knowledge to effectively evacuate the building.

A rare visitor is a victim with less than one knowledge value. This type of victim agent is pre-configured to act as a follower. A rare visitor will always revert to the role of a follower victim. This type of victim will seek out the closest leader to his or her position and then wait for the leader's instruction to evacuate to the building.

The formula to assign the role is according to the knowledge level of a victim. In this case, if the knowledge level reaches a certain threshold, then the victim is assigned as a leader. Otherwise, the victim will be assigned as a follower who follows the routes taken by the leader. After the central system broadcasts the building's emergency status, a knowledge generating process is invoked to ascertain the victim agents' roles. This procedure is only carried out once, at the initial state of evacuation. Finally, the victim agent will be assigned a leader or follower which possess the behaviour as described in Table 3.4.

Table 3.4: Behaviour Description of Leader and Follower

Behaviour	Behaviour Description
Leader	Receives the emergency and path information from the central system and distribute the emergency information to the victims closed to him.
Follower	Receive the emergency information from the leader and evacuate the building by following the leader's moving direction.

Figure 3.4 shows the flowchart of a leader agent. When the alarm goes off, the leader agent will request available route options to exit the door based on the shortest distance. If there are any victims nearby, the leader agent will ask the victim to form a group before leading them to the exit door.

Figure 3.5 shows the flowchart of a follower agent. When the alarm goes off, the follower agent will evaluate by its knowledge level. If the knowledge level is below 1, then the follower needs to wait for the instruction to form a group before leaving the room. Otherwise, the follower can form a group with nearby followers before evacuating the room.

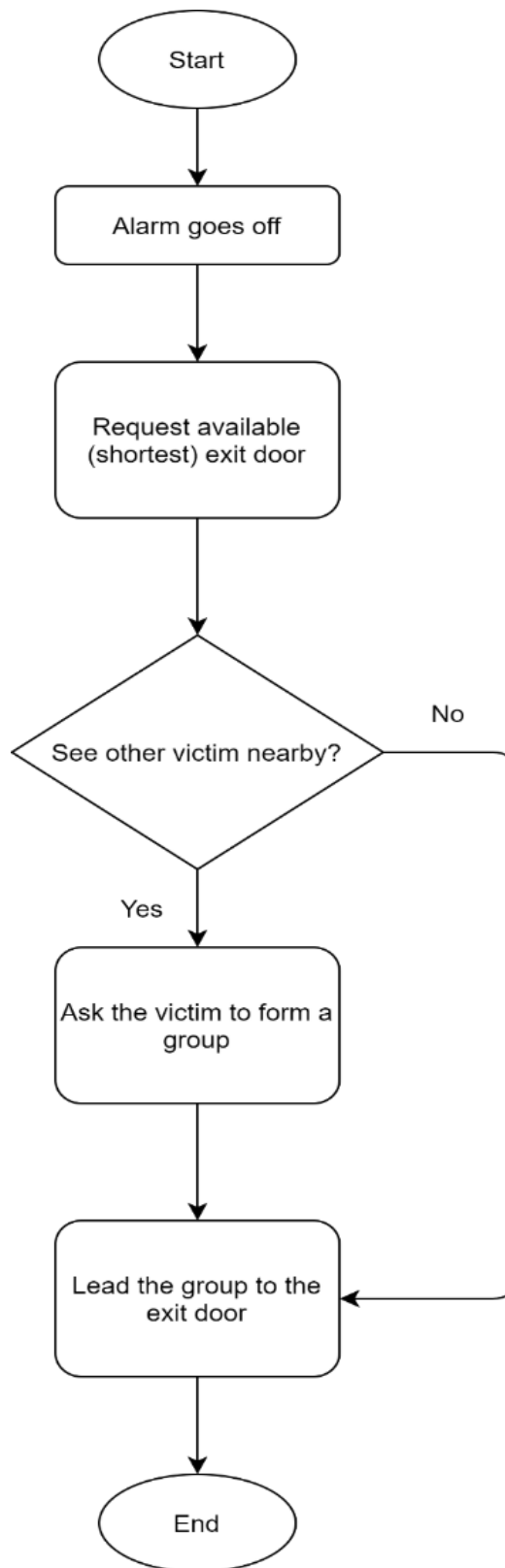


Figure 3.4: Flowchart of a Deliberation of A Leader During The Evacuation Process

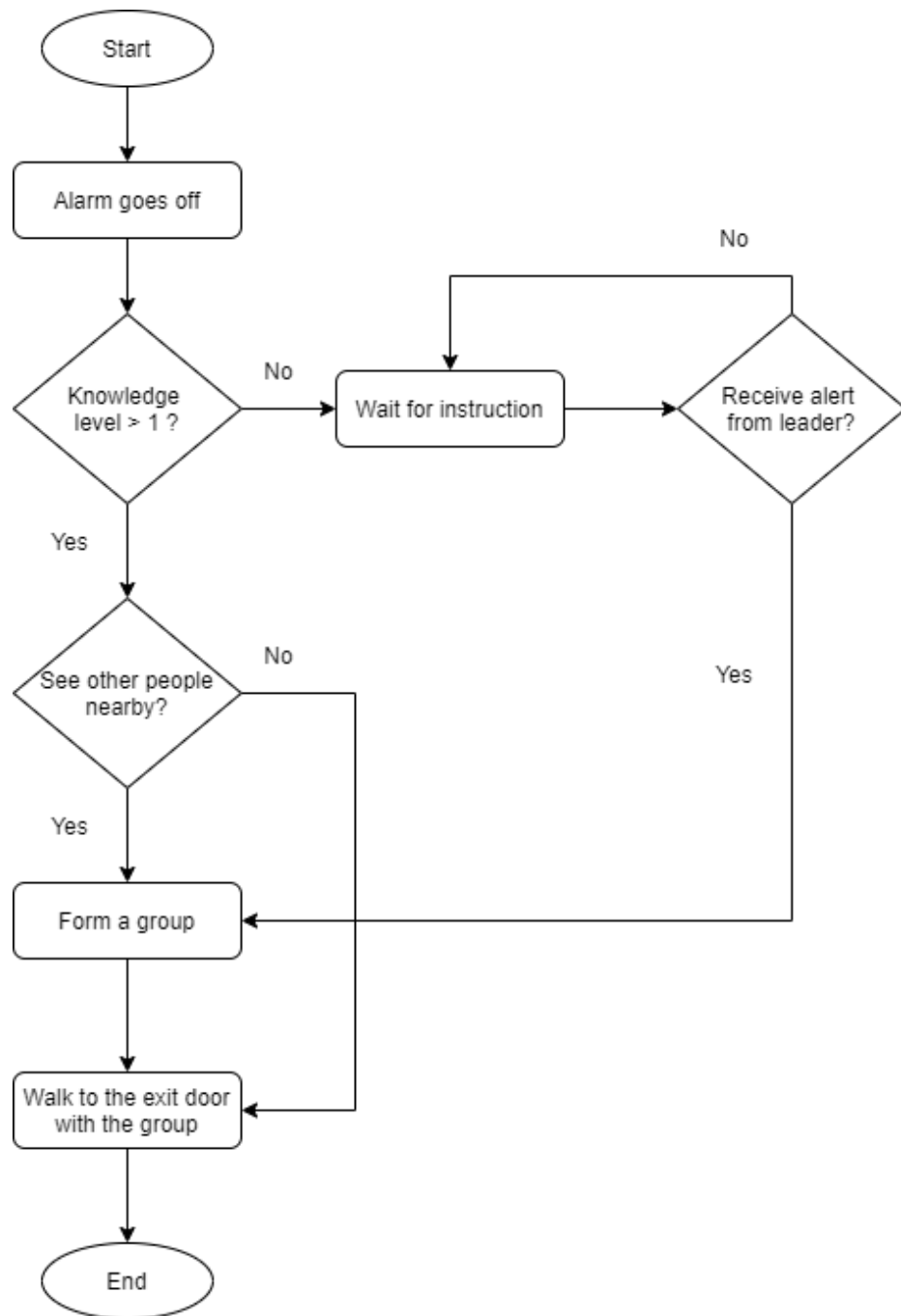


Figure 3.5: Flowchart of A Deliberation Process of A Victim Agent

Algorithm 1: Role Assignment

```
for all victim agents  $v$  do  
    computeKnowledgeValue ( $v$ )  
    if  $v$  has_knowledge_level  $> 1$  then  
        setRoleAsLeader ( $v$ )  
    else  
        setRoleAsFollower ( $v$ )  
    end if  
end for
```

Figure 3.6: Algorithm 1; Role Assignment

We propose an algorithm for role selection as shown in Figure 3.6. The algorithm will classify a victim agent as either a leader or a follower. Before moving on to the next step in the process of role selection, we use this algorithm to assign a score to the amount of knowledge possessed by each victim agent. Then, we determine if the victim agent is a leader or a follower in the group of victims. If a victim agent has a knowledge level that is greater than 1.0, then that victim agent will act in a leadership capacity. If the agent's knowledge level is lower than 1.0, the agent will be placed in the follower role. The procedure for delegating the victim's role is laid out in Figure 3.6; Algorithm 1. The algorithm is derived from some reviews of existing works (Xie et al., 2022; Qingge & Can, 2007).

As stated in Algorithm 1, the first step in the role selection process is to compute the knowledge value for each victim agent. The possibility of any victim agent becoming a leader is computed during the role selection process. For example, Table 3.5 shows the knowledge value that is assigned to various agents. We assumed

that during the early stages of detecting the need to evacuate the building, the central system sends the evacuation information to all victim agents only once. In this process, the knowledge value for each agent will be updated, and the agent's role will be determined after evacuation information has been distributed. When a victim agent receives the evacuation information, its knowledge value is increased by 0.5. It should be noted that this is our own defined value; it can be replaced with another to comply with any specific rules.

Table 3.5: Knowledge Value of Building Personnel, Frequent Visitor, and Rare Visitor

Type of victim agent	Pre-assigned Knowledge Value	Updated Knowledge Value	Knowledge Value	Agent Role
Building personnel	1	0.5	1.5	Leader
Frequent visitor	0.5	0.5	1	Follower
Rare visitor	0	0.5	0.5	Follower

Then, the role selection process will determine the behaviour of victim agent to become either a leader or a follower during the evacuation process.

3.3.4 Movement Module

The movement module handles the computation of the interaction force to gather the actual direction and velocity of the victim. To accomplish this, Social Force Model (SFM) is adopted.

The fundamental components that build the SFM consist of three types of forces; self-driven force, repulsive force, and attractive force. The term "interaction force" refers to both repulsion and attractive forces. The self-driven force reflects the motivation of a pedestrian (P_i) who is moving towards a target location (T) with the desired speed. In contrast, the interaction force is the force that forms the interactions between a pedestrian and another object such as another pedestrian (P_j), including socio-psychological and physical interactions. The repulsive force is deployed to prevent pedestrians from colliding with the walls and with one another. Because of the distance between the two pedestrians, the strength of the repulsive force differs. In contrast to the repulsive force, which is used to separate pedestrians at a certain distance, the attractive force is defined as the force that keeps pedestrians in a group working together to achieve a common goal. Those three forces are structured in such a way that they may be used to calculate the next available place for each pedestrian to move at a given time. Meanwhile, for a pedestrian (P_i) to reach the desired location (T), his or her subsequent footstep will be influenced by the interaction forces that have formed around.

3.3.4.1 Social Force Model Formulation

This section explains the basic formulation of the SFM based on (Helbing et al., 1995). The SFM formulation is depicted in Figure 3.7.

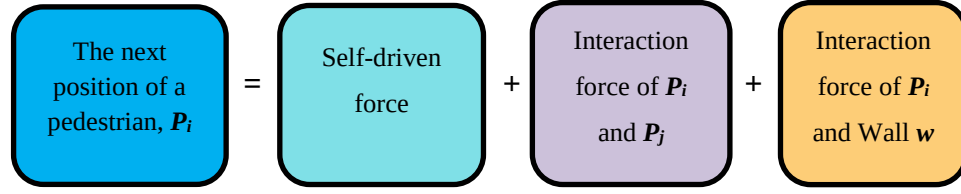


Figure 3.7: Overview of Social Force Model Formulation

According to SFM formulation, the next position of a pedestrian (P_i) is formulated by the summation of three different forces; self-driven force, interaction force of pedestrian (P_i) and pedestrian (P_j), and the interaction force of pedestrian (P_i) and wall (w).

3.3.4.2 Self-Driven Force

Equation 3.1 depicts the computation of self-driven force. The change of velocity for each pedestrian i having a mass M in time T is depending on the self-driven force calculated.

$$\vec{f}_i^0 = m_i \times \frac{\overrightarrow{v_i^0(t) e_i^0(t) - v_i(t)}}{T_i} \quad \text{Equation 3.1}$$

where:

m_i : mass of pedestrian i

v_i^0 : target velocity of pedestrian i

$\vec{e}_i^0$: desired direction of pedestrian i

$\vec{v}_i$: actual velocity of pedestrian i

T_i : relaxation time of pedestrian i

This force is called self-driven force because of the pedestrians having the self-motivation which at the end makes them move until they reach their desired target location. Along the way to the target location, the pedestrians adjust their actual velocity according to their relaxation time towards their desired direction.

3.3.4.3 Interaction Force of Pedestrian

Equation 3.2 calculates the interaction force between pedestrian i and pedestrian j .

$$\vec{f}_{ij} = -A \exp((r_{ij} - d_{ij}) / D) \times \vec{e}_{ij} \quad \text{Equation 3.2}$$

where:

r_{ij} : sum of pedestrians (i, j) radii

d_{ij} : Euclid distance between two pedestrians' centres of mass

$\vec{e}_{ij}$: a normalised vector, the direction of which is from pedestrian j to i

A : constant to measure the magnitude of repulsive force

D : constant to limit the range of repulsive force

3.3.4.4 Interaction Force of Pedestrian and Wall

Equation 3.3 calculate the interaction force of pedestrian i and wall w .

$$\vec{f}_{iw} = -A \exp((r_i - d_{iw}) / D) \times e_{iw} \quad \text{Equation 3.3}$$

where:

r_{ij} : radii of pedestrians i

d_{iw} : Euclid distance between pedestrian i and wall w

e_{iw} : a normalised vector, the direction of which is from wall w to pedestrian i

A : constant to measure the magnitude of repulsive force

D : constant to limit the range of repulsive force

The complete mathematical expression for SFM is shown in Equation 3.4.

$$\frac{d\mathbf{v}_i}{dt} = \mathbf{m}_i \frac{\mathbf{v}_i^0(t) \mathbf{e}_i^0 - \mathbf{v}_i(t)}{T_i} + \sum_{j \neq i} \mathbf{f}_{ij} + \sum_w \mathbf{f}_{iw} \quad \text{Equation 3.4}$$

where:

$\mathbf{m}_i$: mass of pedestrian i

$\frac{\mathbf{v}_i^0(t) \mathbf{e}_i^0 - \mathbf{v}_i(t)}{T_i}$: self-driven force of pedestrian i

$\sum_{j \neq i} f_{ij}$: interaction force of pedestrian i and pedestrian j

$\sum_w f_{iw}$: interaction force of pedestrian i and wall w

We can transform the SFM formulate into the pseudocode as following:

Step 1: Compute the self-driven force.

(a): Compute mass of pedestrian i

(b): Compute desired speed

(c): Compute desired direction of movement

(d): Compute actual velocity with relaxation time

let repx 0

let repy 0

let hd heading-to-exit-door

let h heading-to-exit-door

let k 0.0024

if not (speedx * speedy = 0)

[set h atan speedx speedy]

Figure 3.8: NetLogo Code Snippet to Compute Step 1 of SFM

Step 2: Compute the interaction between pedestrians (repulsive force) and wall.

(a): Compute sum of radius of pedestrian *i* and *j*

(b): Compute the normalised vector pointing from pedestrian *j* to *i*

(c): Compute range of repulsive interaction

```
ask turtles in-radius (2 * D) with [not (self = myself)] [  
  set repx repx + A * exp((1 - distance myself ) / D ) * (k + sin(towards  
myself ) * ( k + (1 - cos(towards myself - h)) ))  
  set repy repy + A * exp((1 - distance myself ) / D ) * (k + cos(towards  
myself ) * ( k + (1 - cos(towards myself - h)) )) ]  
  
  set speedx speedx + dt * (repx + (desired-velocity * sin hd - speedx) /  
relax-time )  
  
  set speedy speedy + dt * (repy + (desired-velocity * cos hd - speedy) /  
relax-time ) ]
```

Step 3: Add the result of the preceding calculations.

```
ask peds [  
  set heading towards one-of seen-exit  
  
  set xcor xcor + speedx * dt  
  
  set ycor ycor + speedy * dt  
]
```

Figure 3.9: NetLogo Code Snippet to Compute Step 2 and Step 3 of SFM

The movement module also involves the communication of victims during the evacuation process. There are two different kinds of agent communication; leader and follower communication, and leader and central system communication. The victim agent will be informed by the central system during the emergency about the status of the situation and whether they need to evacuate during the disaster. The leader will then send out a request for the routes that will be used for the evacuation from the central system. The leader then transfers the routes information to the follower, during which they are instructed to follow the leader's instructions on the evacuation of the building.

To allow the message passing activities between the victim agents, we define Algorithm 2 that describes the message passing activity between agents in the simulation model. The message between agents contains the status of emergency, and either agents need to evacuate or not.

Algorithm 2: Message passing between victim agent

```

if any? neighbours within the specified radius then
    pass the message
else
    keep moving towards the exit door
end if

```

Figure 3.10: Algorithm 2; Message Passing Between Agents

In Algorithm 2, the message passing occurs among the victim agents. The message will be passed by the leader agent to any follower agents within the preferable radius from the leader. Meanwhile, the follower agent will pass the message to any neighbour victim agents, if they encounter any.

The following section describes the details of the communication between agents. When a hazard is found in the building, the central system will send a message to all victim agents informing them about the situation (Figure 3.11). The central system will request the role of the victim agent. Only the leader will send the message back to central system to inform his role. Then the leader will send request to the central system asking for the closest exit to be used. After that, the leader will receive a message from the central system informing the closest exit door should be used. Finally, the leader will inform the followers by sending the message related to evacuation instruction (Figure 3.12).

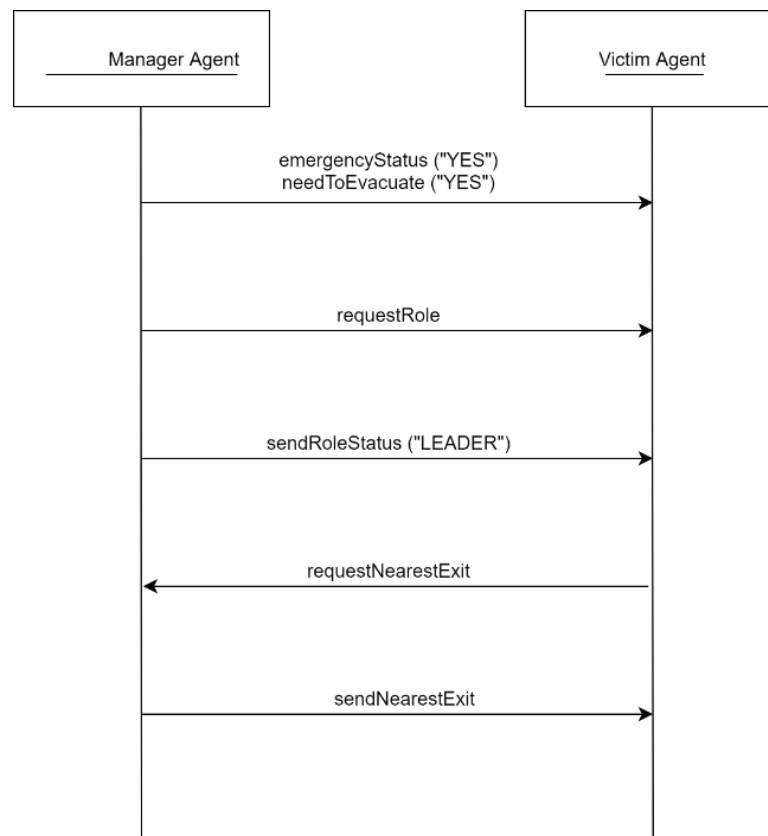


Figure 3.11: The Interaction Diagram of A Central Manager Agent And Victim Agent

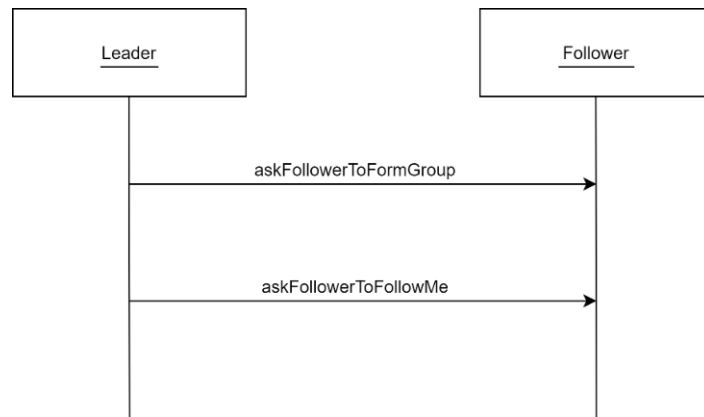


Figure 3.12: Message Passing Between A Leader And A Follower (Receiver)

3.4 Simulating The Room Evacuation

This section describes the implementation of simulating the building evacuation using the proposed agent crowd steering simulation model that involves the use of the original Social Force Model. This finding will be used as the benchmarking experiment on the proposed agent crowd steering simulation model. The findings cover the investigation of the following:

- i. The relationship between the number of victims and the overall time required forevacuation.
- ii. The relationship between the number of exits and the overall time required forevacuation.
- iii. The relationship between the desired velocity and the overall time required forevacuation.
- iv. The relationship between the radius of message spread and the total number of victims.

These relationships are important observations to validate the results with the previous studies done by some researchers (Li et al., 2019; Liu et al., 2016). Moreover, any emergent phenomena that may occur during the simulation run will be observed.

3.4.1 Model Assumption

The model is built based on the following assumptions:

- i. There is no visible fire or smoke in the room.
- ii. Every victim agent will evacuate the room when the alarm goes off.

3.4.2 Agent's Setting

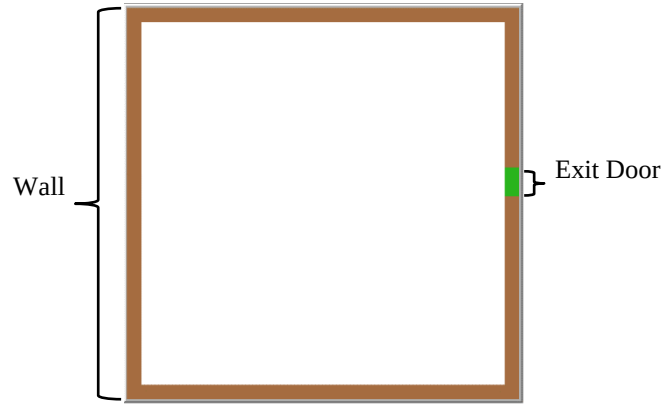
In the experiment, all victim agents are specified as being aware of their surroundings and aware of the exit door. As a result, when the alert sounds, all victim agents will begin to evacuate.

3.4.3 Layout Design

The experiments consist of two room layouts; 1) a room with one exit door and 2) a room with two exit doors. The SFM proposed by Helbing et al. (2000) is used and a NetLogo- based algorithm is implemented in this experiment.

In the experiment, the size of the room is 25×25 patches, including the walls. For both parts of the simulation, the number of victims involved was 100, 200, 300, 400, and 500. The room is designed as shown in Figure 3.12. The brown line is the wall, and the green line represents the exit door. In this simulation model, the evacuation started when the alarm sound went off. The layout design with a single

exit door has been proposed in many previous studies, such as proposed by Li et al. (2019).



Legends:

Brown Line		Wall/Static Obstacles
Green Line		Exit Door

Figure 3.13: The Design of The Simulation Layout

3.4.4 Parameter Settings

The specification for the SFM models followed the work done by Helbing et al. (2000), as discussed in Section 3.4.2.1. Under the panic conditions, the velocity (Desired Speed or DV) of people leaving the room could increase from 1 to 1.5 ms^{-1} . The parameters used in the experiment are shown in Table 3.6.

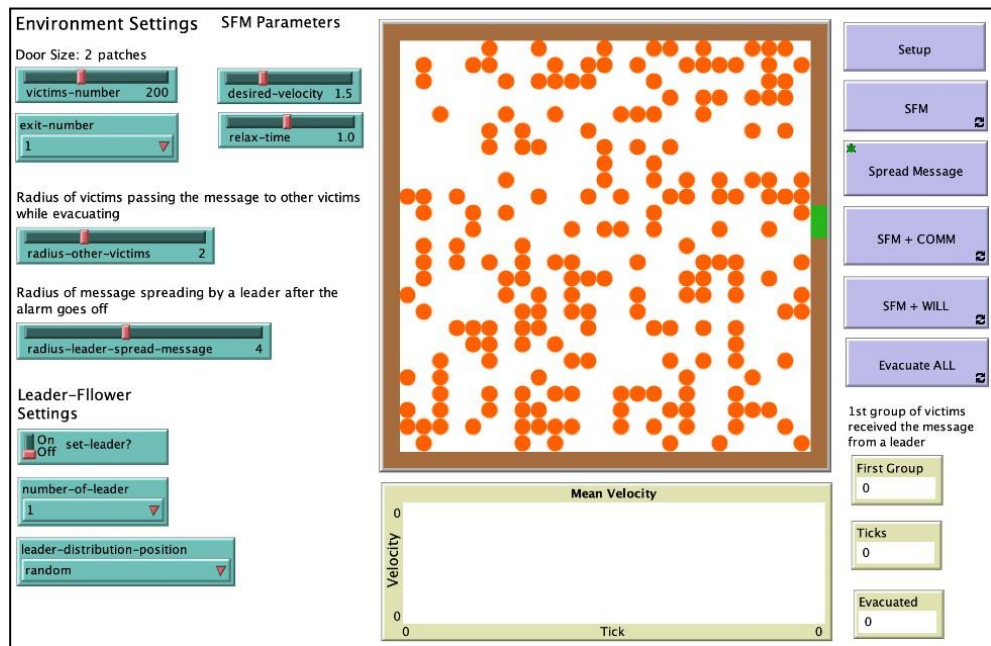


Figure 3.14: The NetLogo Interface for The Simulation

Table 3.6: The Parameters Settings Used in The Experiments

SFM Parameters	Settings	Remarks
Constant A (Repulsive Strength)	1.0	Determines the strength of the repulsive force between pedestrians. The value 1.0 is optimum to avoid agents standing too close to each other (agents overlap). Higher value will move agents far from each other.
Constant B (Repulsive Range)	0.5	Affect the range or distance over which the repulsive force acts. The value is optimum to avoid agents standing too far from each other.

Table 3.6: continued

Relaxation Time	1.0	Refers to the time it takes for a pedestrian to adjust their speed and direction in response to the social forces acting upon them. Typical values are 0.5 – 1.0s.
Desired Velocity	1, 1.5	Represents the speed and direction an individual pedestrian aims to move towards their intended destination, independent of other people and obstacles. Typical values are 1.2 – 1.5 ms⁻¹ for normal situation.
Derivative Time	0.05	Refers to the time derivative of a pedestrian's position, which is essentially their velocity. The value refers to how an agent's velocity changes over time. The time derivative is numerically integrated using small steps such as 0.01s, 0.05s, or 0.1s. The value 0.05 generate more precise and slower simulation but smoother motion.
Number of Victims	100, 200, 300, 400, 500	The number agents are set to be between 100 and 500.

3.4.5 Simulation and Result Analysis

The simulation model was developed and run for multiple series of evacuation experiments. The experiments were performed using a laptop with Intel Core i5 3.1 GHz CPU with 8 GB RAM. The time for evacuation is measured using the NetLogo simulation unit Tick.

Table 3.7 depicts the screenshot of simulations at ticks = 100 and ticks = 500 for the two experiments involving 100, 200, 300, 400, and 500 number of people in the simulation. N is the number of victim agents in the simulation, and DV is the desired velocity of agents. From the simulation screenshots, as shown in Table 3.7, the evacuation pattern at the exit door is like the one produced in the work of Helbing et al. (2000). The arching phenomena is clearly shown, and this proves that our proposed agent crowd steering simulation model can steer the victim to exit door.

Table 3.7: Screenshot of Simulations

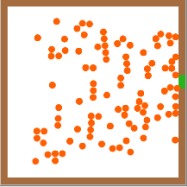
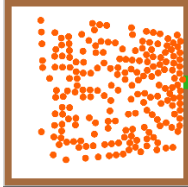
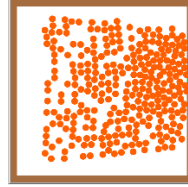
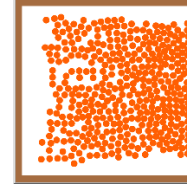
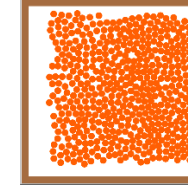
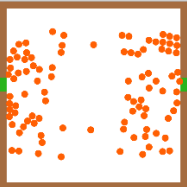
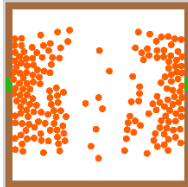
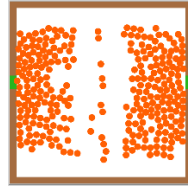
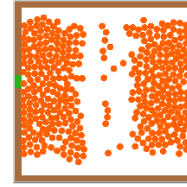
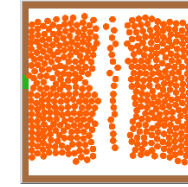
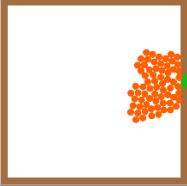
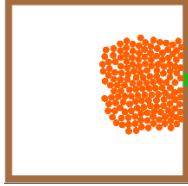
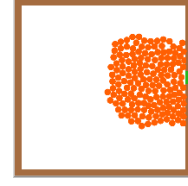
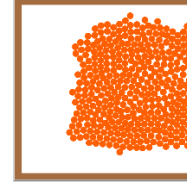
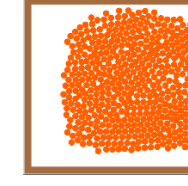
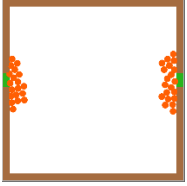
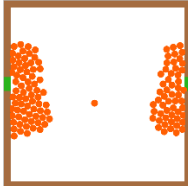
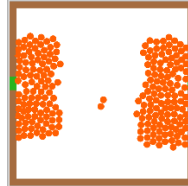
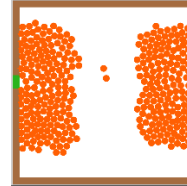
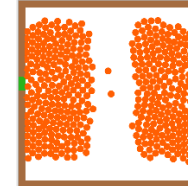
DV = 1.0		N = 100	N = 200	N = 300	N = 400	N = 500
Ticks = 100	SingleExit					
	MultipleExits					
Ticks = 500	SingleExit					
	MultipleExits					

Table 3.8: The Evacuation Time in Ticks for Each Scenario

	Single Exit		Multiple Exits	
N	DV = 1.0 ms ⁻¹	DV= 1.5 ms ⁻¹	DV = 1.0 ms ⁻¹	DV = 1.5 ms ⁻¹
100	1444	917	955	564
200	2747	1750	1563	998
300	4024	2578	2271	1430
400	5322	3406	2897	1847
500	6600	4230	3592	2298

According to Table 3.8, For a single exit scenario, the percentage reduction in evacuation time when DV is increased from 1.0 to 1.5 is 36% for each N. Meanwhile, the percentage reduction in evacuation time differs for scenarios with multiple exits. For N = 100, the decrease is 41%; for N = 200, it is 36%; for N = 300, it is 37%; for N = 400, it is 36%; and for N = 500, it is 36%. The decrease in percentage is between 37% and 41%, which is nearly identical to the single exit scenario.

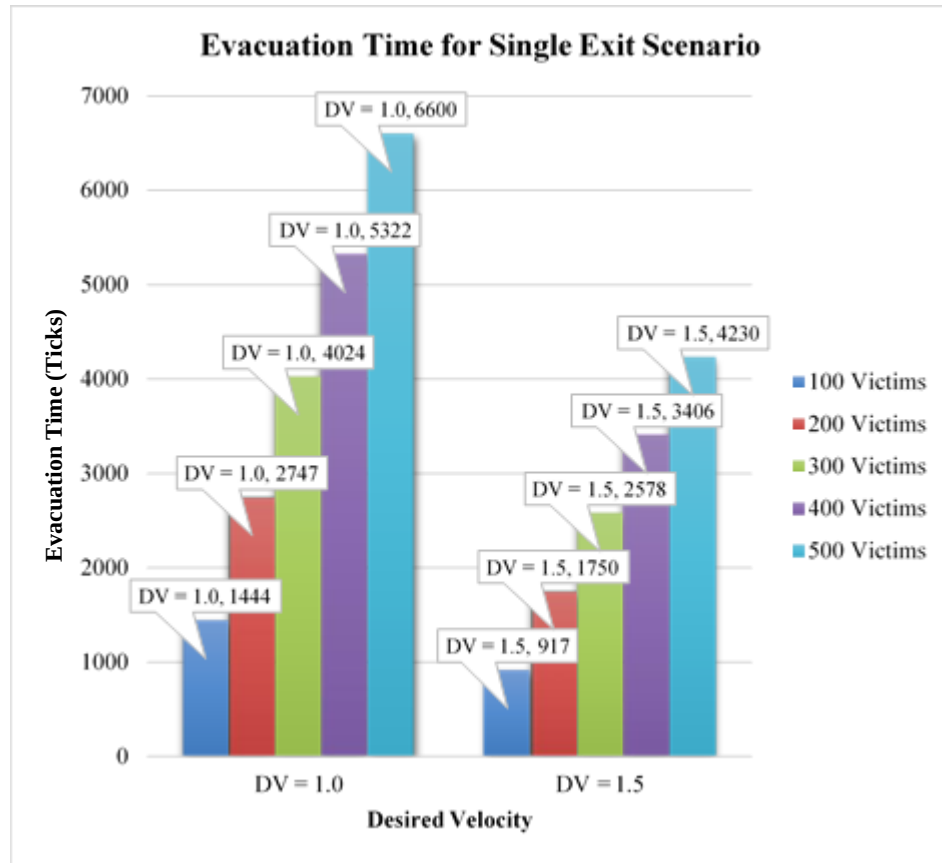


Figure 3.15: Total Evacuation Times for Single Exit Scenario using $DV = 1.0 \text{ ms}^{-1}$ and $DV = 1.5 \text{ ms}^{-1}$

As illustrated in Figure 3.15, when the desired velocity (DV) is increased to 1.5 ms^{-1} , the evacuation time for each simulation scenario involving five different types of victims decreases. As illustrated in Figure 3.16, the same decreasing trend occurs in the scenario with multiple exits.

When switching from a single exit to several exits in a $DV = 1.0$ scenario, the percentage decrease in evacuation time is between 34% and 46%. The drop is 34% for $N = 100$, 43% for $N = 200$, 43% for $N = 300$, 44% for $N = 400$, and 46% for $N = 500$. For $DV = 1.5$, the percentage reduction in evacuation time is 38% for $N = 100$, 43% for

N = 200, 43% for N = 300, 46% for N = 400, and 46% for N = 500. For both DVs, the same diminishing trend occurs for N = 400 and N = 500. As of present, it can be established that when N exceeds 400, a similar pattern of decreasing evacuation time occurs. However, for this experiment, we can only limit N to 500 since that is the maximum population size that the simulation room design can accommodate.

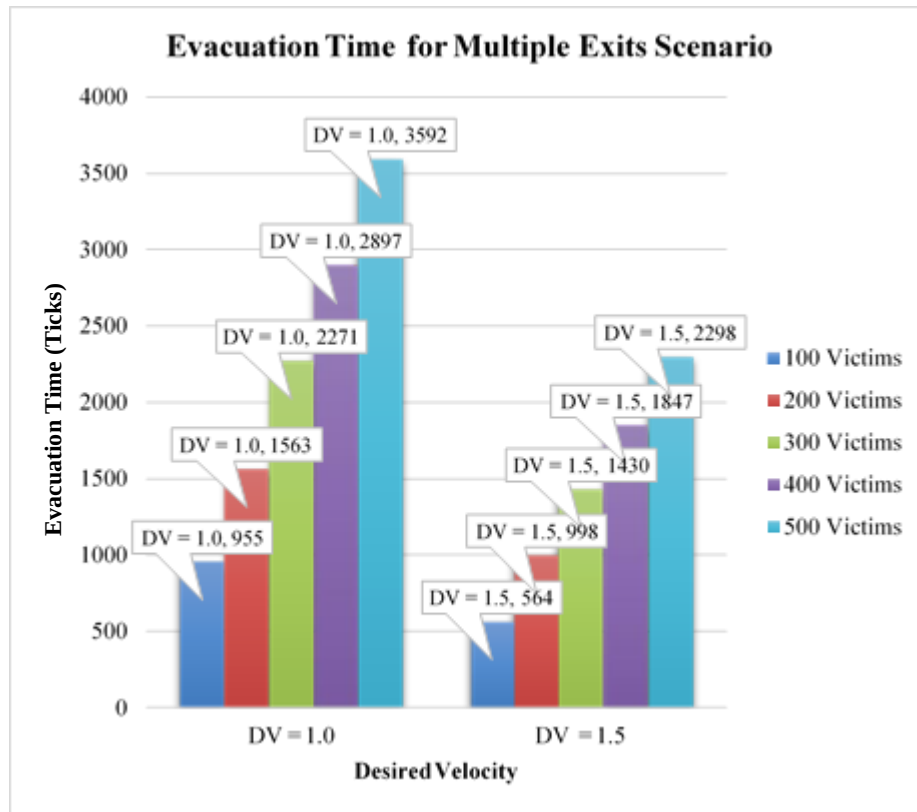


Figure 3.16: Total Evacuation Times For Multiple Exits Scenario using DV = 1.0 ms⁻¹ and DV = 1.5 ms⁻¹

Table 3.9 depicts the decreased percentage of evacuation time when using multiple exits as compared to single exit. N is number of victim agents in the simulation, and DV is desired velocity of agents. The formula used to calculate the decrease percentage is starting

value (value of evacuation ticks when $DV = 1.0$) minus the ending value (value of evacuation ticks when $DV = 1.5$). The result is then divided by starting value. Then, the result will be times to 100. As shown in Table 3.9, the use of multiple exits could reduce the evacuation time from 34% to 46% for both scenario ($DV = 1.0 \text{ ms}^{-1}$ and $DV = 1.5 \text{ ms}^{-1}$), depending on the number of victims involved.

Table 3.9: The Decreased Percentage of Evacuation Time When Using Multiple Exits as Compared to a Single Exit

N	$DV = 1.0 \text{ ms}^{-1}$	$DV = 1.5 \text{ ms}^{-1}$
100	34%	38%
200	43%	43%
300	44%	45%
400	46%	46%
500	46%	46%

It is shown in Table 3.9 that the decrease percentage when using $DV = 1.0$ and $DV = 1.5$ is insignificant between the two settings. For example, when $N = 400$ and 500 , the decrease percentage is 46% for both DV settings.

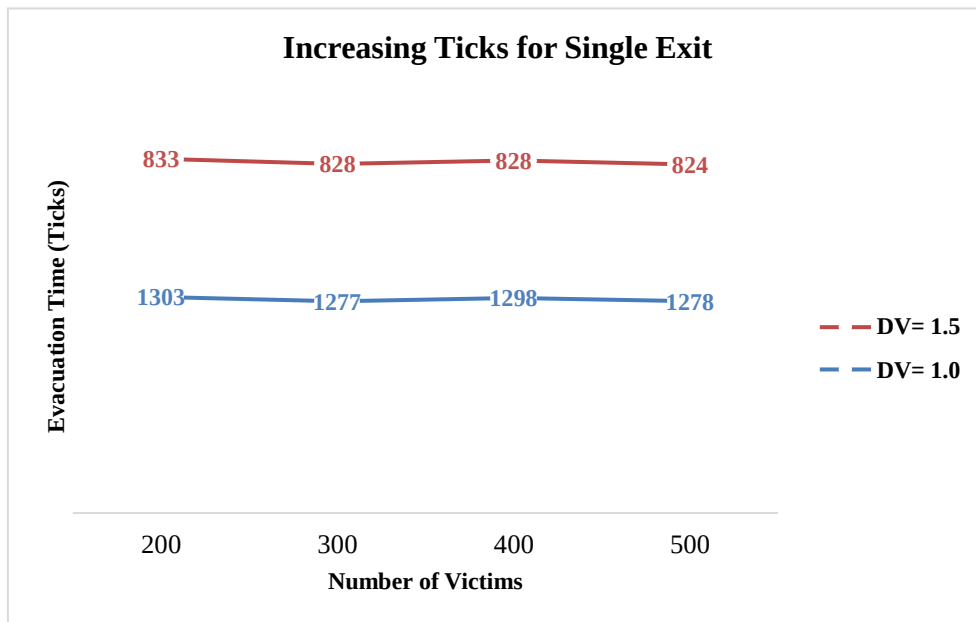


Figure 3.17: The Trend in Evacuation Time for A Single Exit Scenario

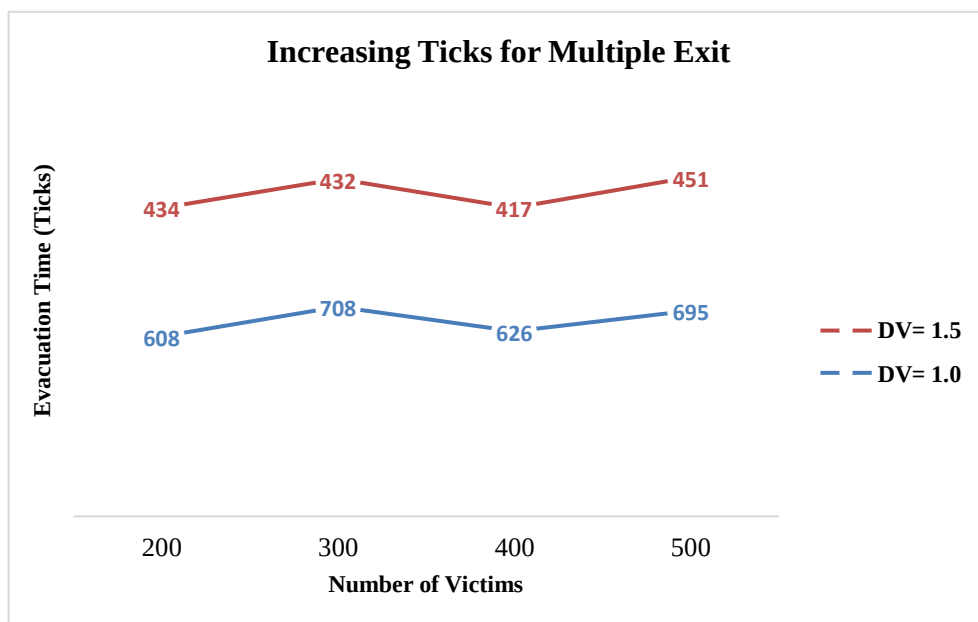


Figure 3.18: The Trend in Evacuation Time for Multiple Exits Scenario

When N is increased to 200, 300, 400, and 500, the evacuation time increases linearly for both $DV = 1.0$ and $DV = 1.5$. However, in the scenario with two exits, the increasing tendency is unstable, with two instances where evacuation times dropped little and subsequently increased slightly. These incidents could be the result of an uneven distribution of victims using both exit doors.

3.5 Discussion

This chapter proposes an agent crowd steering simulation model for mobile crowd simulation. It covers the module design and algorithm design. The agent crowd steering simulation model is further developed using the NetLogo simulation platform. In this case, the original SFM is developed for a fire evacuation case study to form the benchmarking experiment for the rest of the module development in the following chapters.

In the experiment of a single exit scenario, the percentage reduction in evacuation time when DV is increased is 36%. However, in the scenario with two exits, the increasing tendency is unstable, with two instances where evacuation times dropped little and subsequently increased slightly. The decrease in percentage is between 36% and 41%, which is nearly identical to the single exit scenario. As of present, it can be established that when N exceeds 400, a similar pattern of decreasing evacuation time occurs.

The simulation results produced in this chapter are then compared to the simulation results in the existing studies. We compared our results with the study conducted by Flores et al. (2024). Flores et al. introduced the studies of SFM to explore pedestrian behaviour during tsunamigenic earthquakes. The research adopted original

SFM model as pedestrian motion methods and the simulation are implemented in NetLogo. As the authors selected the state-of-the-art crowd evacuation method, it is sensible to validate the SFM model that is developed and simulated in this chapter.

The following table highlights the key comparison for both simulations. For the comparison purpose, we converted the number of ticks to second and assumed that 1 patch in NetLogo equals to 0.3 meter. The conversion of patch to meter is adopted from study by Liu et al. (2015). The room size that we designed in this experiment is 25x25 patches including the walls. Thus, the room size is 23 (width) x23 (length) patches and equals to 158.7 square meters. We also assumed that 1 tick in NetLogo equals to 0.033 second, which means that 100 ticks in NetLogo equals to 3.3 second. This tick to second conversion follows the settings by Flores et al. (2024), for comparison purpose.

Table 3.10: The Key Comparison of Evacuation Simulation

	Study in this thesis	Flores et al. (2024)
People	100	100
Type of Simulation Layout	A square room	A corridor
Layout Design (Length and Width)	23 x 23	51 x 13
Simulation Area	158.7m ²	198.9m ²
Exits	1	1

Table 3.10: continued

Evacuation Time	30.26s	53.77s
Desired Velocity	1.5m/s	Near to 2.77m/s

From the comparison in Table 3.10, both studies simulated evacuations with 100 individuals. In study conducted by Flores et al. (2024), the area of simulation layout is designed to be 198.9 m², which is slightly larger than our room size. In term evacuation time, our simulation results achieved a faster evacuation time compared to study conducted by Flores et al. (2024). The reason for faster evacuation time is due to the simulation layout design. Our simulation layout design is 23 patches for length and width. Hence the distribution of the evacuee location in the simulation area is scattered almost evenly. This results in the shorter travel time from the starting position to the exit door, as compared to Flores et al. (2024). Their evacuee started the journey from the left side of the simulation area and heading to exit door on the right side. Thus, the evacuee took the longer travel distance from the starting position to the exit door.

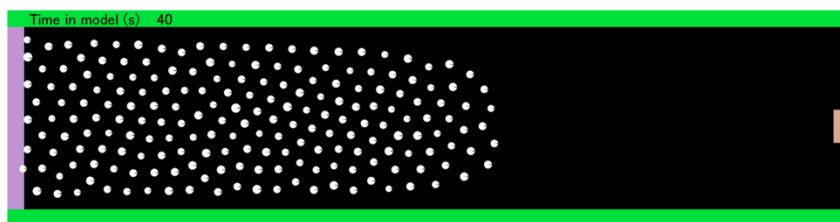


Figure 3.19: The Simulation Layout in Flores et al. (2024) With 200 Agents

The analysis reveals that evacuation efficiency is significantly affected by the design of the layout and the initial distribution of evacuees. The more equal distribution in the

current study's simulation resulted in reduced travel lengths and accelerated evacuation times relative to the layout employed by Flores et al. (2024). This indicates that the strategic positioning of individuals within a space might improve evacuation efficiency, even in somewhat smaller regions.

3.6 Chapter Summary

The simulation evacuation model developed in this thesis adopts the Design Science Research Process (DSRP) framework to design, implement, and evaluate a mobile crowd steering simulation system for emergency evacuations. The research addresses the limitations of existing crowd steering systems, particularly their inability to adapt to unpredictable real-world events such as communication disruptions. The proposed solution includes an agent-based simulation model simulated using NetLogo, emphasizing the integration of contextual, demographic, and communication factors. The model consists of four core modules; context manager, path planning, role selection, and movement. Victim agents are assigned as either leaders or followers based on knowledge levels and role suitability. The simulation leverages the Social Force Model (SFM) to govern pedestrian motion through self-driven, repulsive, and attractive forces. Communication between agents, particularly message propagation from leaders to nearby agents, simulates real-world word-of-mouth scenarios. Evaluation experiments tested evacuation performance across different numbers of agents, exit configurations, and desired velocities. The results revealed that increasing velocity and using multiple exits significantly improved evacuation times, with observed reductions of up to 46%. Comparative analysis with the work of Flores et al. (2024) showed that layout design and initial agent distribution substantially influenced evacuation performance,

validating the simulation's accuracy and relevance. This chapter underscores the importance of spatial design, agent interaction, and dynamic modelling in improving emergency evacuation systems. The results are important to benchmark and validate the rest of the modules that are developed for agent crowd steering simulation model as described in the next chapter.

CHAPTER 4

THE AGENT MESSAGING MODEL

4.1 Introduction

This chapter presents the agent communication model. The messaging model incorporates the ability of victim agents to spread messages among them whenever an evacuation instruction is received. The model is the communication module that is presented agent crowd steering simulation model, as stated in Chapter 3. Section 4.2 presents the agent's communication design where we defined leader and follower agent's communication. Section 4.3 describes the experiments that we conducted involving setting up the agent's characteristic as building personnel, frequent visitor, and rare visitor. This section also presents the simulation results and analysis. Section 4.4 explains the threat validation for the experiments conducted in this chapter. Finally, Section 4.5 describes the summary of this chapter and the discussion.

4.2 Agent's Communication Design

An agent messaging model is utilised in crowd steering simulation to enhance communication and coordination among individual agents in the simulated crowd. The objective of this model is to replicate real-life situations in which individuals within a group engage in the exchange of information, signals, or cues in order to navigate efficiently and collectively react to different stimuli or goals. The Agent messaging model significantly improves the authenticity and efficacy of crowd steering simulations by replicating the communication and coordination mechanisms observed in actual crowds. This technology facilitates the examination and enhancement of crowd

behaviour, safety, and efficiency across diverse contexts by researchers and practitioners.

In this model, the spreading of the message is performed by the leader and the victim agent, who is categorised as a frequent visitor. Both types of agents have a knowledge value of 1 and above. Even though the frequent visitor has the role of a follower, the ability to spread the message is assigned according to computed knowledge value. As explained in the previous chapter, the agent role is assigned to the victim agent according to the knowledge value derived by adding the pre-assigned knowledge value and updated knowledge value. The agent that has a knowledge value of 1 and above is assigned as a leader, otherwise as a follower.

During the evacuation, a leader and frequent visitor can spread the message within a certain proximity. The spreading of the message is using the word-of-mouth (WOM) method. In crowd simulation, the WOM approach denotes a communication system whereby information, including the location of exits, obstacles or hazards, disseminates through agent-to-agent interaction, similar to verbal information sharing in real-life scenarios. In this method, the victim agent will communicate with the other victim agent (referring to those who have a knowledge value of 1 or more) while heading to the nearest exit door. As the victim agent approaches the exit, they will inform nearby victim agents of the urgent need to vacate the room promptly due to an emergency.

The Word-of-Mouth (WOM) method in evacuation simulation refers to the informal communication process where agents (individuals) pass on information about the emergency situation; such as the need to evacuate, the direction of exits, or the presence of hazards; to nearby agents within a defined communication radius. This

method mirrors real-life scenarios where people often rely on social cues, verbal interactions, or the observed actions of others during emergencies. In the simulation, when an agent who is already aware of the evacuation need (typically a leader or a quick-reacting individual) comes into close proximity with an unaware agent, the message is transmitted. This changes the state of the receiving agent from unaware to aware and may influence their behaviour, such as initiating movement toward an exit or joining a group. The newly informed agents then continue to relay the message to others within range, forming a chain of communication. The effectiveness of WOM depends on several factors including agent density, the defined radius for communication, the willingness and behaviour of agents, and their individual traits; such as panic or adaptability. For instance, panic agents may not effectively spread the message, while resourceful or quick-learning agents are more likely to do so. Overall, WOM communication significantly impacts evacuation dynamics by enabling emergent group behaviours and influencing the speed and coordination of movement during critical events.

Crowd behaviour is influenced by a single person's personality trait. The qualities of the people that make up a crowd in a certain setting are, therefore, important to comprehend. We categorised behaviour of victims into four types: panic, resourceful, quick learner, and high adaptability based on the study by Pelechano et al. (2006). A panic victim has a sudden, uncontrollable fear or worry, which can lead to irrational behaviour. A resourceful victim can solve problems quickly and ingeniously. A quick learner is a person who can absorb new information quickly. A high-ability victim is a person who can adapt to changing situations.

Table 4.1: Types of Victims and Behaviour Description

Type of Victims	Behavioural Categorization			
	Panic	Resourceful	Quick Learner	High Adaptability
Trained Leader		✓	✓	✓
Untrained Leader	✓		✓	✓
Panic Follower	✓			
Non-Panic Follower			✓	✓

In our design as stated in Table 4.1, the quick learner and high adaptability are assigned to trained leader, untrained leader, and non-panic follower. These types of victims are able to spread the message through WOM when the evacuation occurs.

The categorisation of victim types in this study was derived from the understanding that individual personality traits significantly influence crowd behaviour, especially during high-stress situations such as emergency evacuations. Drawing from psychological and behavioural research, the diversity in human responses to crisis situations can be broadly represented through four behavioural archetypes: panic, resourceful, quick learner, and high adaptability. These categories were selected to reflect key dimensions of human decision-making, coping capacity, and adaptability under pressure.

The panic type represents individuals who experience acute emotional distress, leading to irrational actions that may hinder evacuation efficiency. This type is critical

to model, as real-life evacuations often include individuals who become overwhelmed and fail to follow logical escape routes. The resourceful type embodies individuals with problem-solving abilities, capable of managing unexpected challenges by identifying alternate exits or guiding others. Quick learners are those who can rapidly process new information or instructions during dynamic situations, a trait essential in adapting to new environments or escape strategies. Lastly, high adaptability refers to individuals who can adjust to changing conditions, such as crowd density or blocked exits, ensuring continued progress toward safety.

Table 4.1 maps these behavioural types to corresponding victim roles to enhance realism and behavioural diversity within the simulation. For instance, trained leaders are assigned all behavioural traits except panic, reflecting their preparedness, leadership, and communication ability. Untrained leaders may panic initially but still exhibit adaptability and learning capability once engaged. Panic followers reflect the subset of evacuees who are highly susceptible to fear and are unlikely to contribute to message dissemination. In contrast, non-panic followers are more receptive, capable of learning and adapting, making them valuable in crowd communication via word-of-mouth (WOM).

This behavioural classification thus enables a nuanced simulation of group dynamics and information flow. It ensures that not all agents act homogeneously and allows the model to realistically assess the impact of behavioural variability on evacuation efficiency, especially in scenarios involving indirect communication and group steering.

There are two different kinds of agent communication; leader and follower communication and leader and central system communication. The victim agent will be informed by the central system during the emergency about the status of the situation and whether they need to evacuate during the disaster. The leader will then send out a request for the routes that will be used for the evacuation from the central system. The leader then transfers the route information to the followers, during which they are instructed to follow the leader's instructions on the evacuation of the building.

To enable the message-passing activities between the victim agents, we define Algorithm 1 in Figure 4.1. The algorithm describes the message-passing activity between agents in the simulation model. The message between agents contains the status of the emergency and whether agents need to evacuate or not.

Algorithm 1: Message passing between victim agent

```

if any? neighbours within the specified radius, then
    pass the message
else
    keep moving towards the exit door
end if

```

Figure 4.1: Algorithm 1

The message passing occurs among the victim agent, that is, from a leader agent to any follower agent, which positions within the preferable radius from the leader. On the other hand, there will be message-passing activities occur among the follower agents during the evacuation towards the exit. In this case, the follower agent will pass the message to any neighbouring victim agents if they encounter any.

The following section describes step-by-step the communication between agents. When a hazard is found in the building, the central system will send a message to all victim agents informing them about the situation (Figure 4.2). The context manager will request the role of the victim agent. Only the leader will send the message back to the context manager to inform his role. Then, the leader will send a request to the central system asking for the closest exit to be used. After that, the leader will receive a message from the context manager informing the closest exit door should be used. Finally, the leader will inform the followers by sending a message related to evacuation instructions (Figure 4.3).

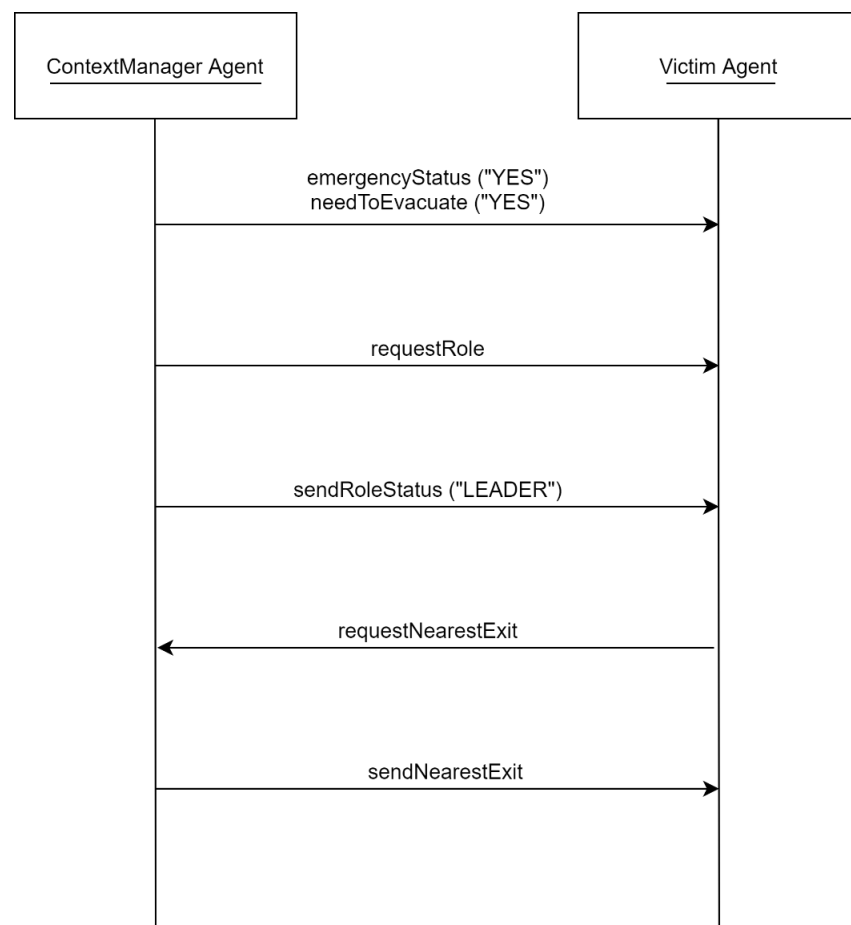


Figure 4.2: The Interaction Diagram of a Context Manager Agent and Victim Agent

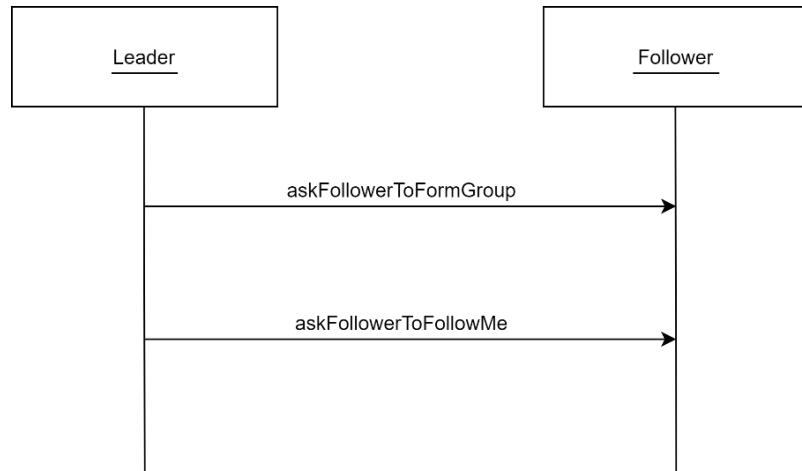


Figure 4.3: Message Passing Between A Leader (sender) And A Follower (receiver)

4.3 Simulating the Room Evacuation

This section describes the experiment that was performed. The experiment conducted to ensure that the proposed communication model is workable. Furthermore, the experiment was designed to look at the relationship between the radius of message spread, role selection, and the overall number of victim agents who joined as a group. Moreover, any emergent phenomena that may occur during the simulation run will be observed.

4.3.1 Model Assumption

The model is built based on the following assumptions:

- i. There is no visible fire or smoke in the room.
- ii. Every victim agent will evacuate the room when the alarm goes off.

4.3.2 Agent's Setting

In this experiment, we created victim agents with the characteristics of building personnel, frequent visitors, and rare visitors. As a result, the three profiles will have varying degrees of knowledge value.

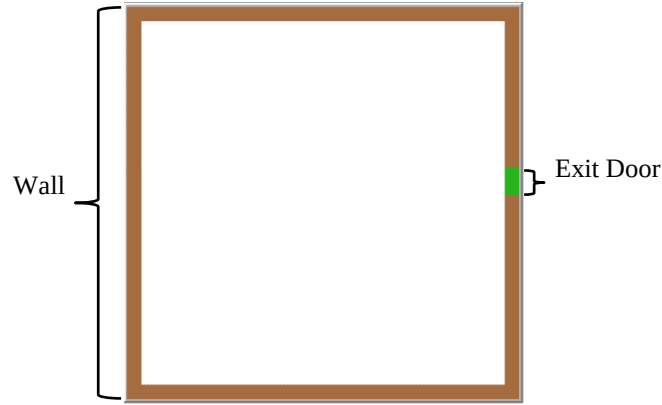
Table 4.2: Agent's Setting Description

Characteristic	Experiment B
Types of Agents	- Building personnel - Frequent visitor - Rare visitor
Knowledge Level	- Building personnel and frequent visitors have a knowledge level of 1.0 or more. - Rare visitor has a knowledge level of less than 1.0.

4.3.3 Experiments Setting

The experiments consist of two room layouts: 1) a room with one exit door and 2) a room with two exit doors. The NetLogo is used as our simulation tool. The size of the room is 25×25 patches, including the walls. For both parts of the simulation, the number of victims involved was 100, 200, 300, 400, and 500.

The room is designed as shown in Figure 4.4. The brown line indicates the wall, and the green line represents the exit door. In this simulation model, the evacuation started when the alarm sound went off.



Legends:

Brown Line		Wall/Static Obstacles
Green Line		Exit Door

Figure 4.4: The Design of a Simulation Layout with Single Exit

4.3.4 Parameter Settings

The specification for the SFM models followed the work done by Helbing et al. (2000). Under panic conditions, the velocity (desired speed) of people leaving the room could increase from 1 to 1.5 ms^{-1} . The justification of using all the values in each parameter as in Table 3.6 (Chapter 3). The additional parameter used in this experiment is the radius of the message spread by the followers and the leader.

Table 4.3: The Parameter Settings Used in This Experiment

Parameters	Settings
Constant A	1.0
Constant B	0.5

Table 4.3: continued

Relaxation Time	1.0
Desired Velocity	1, 1.5
Derivative Time	0.05
Number of Victims	100, 200, 300, 400, 500

Figure 4.5 shows the NetLogo interface that we designed for the room evacuation simulation experiments. We provided some variables for the parameter settings that can be used for specific purposes using the slider tool. The slider tool is available for changing the value of victim number, exit number, desired velocity, relaxation time, radius to another victim, radius of leader spreading the message, and number of leaders. Noted that desired velocity and relaxation time are under SFM parameters.

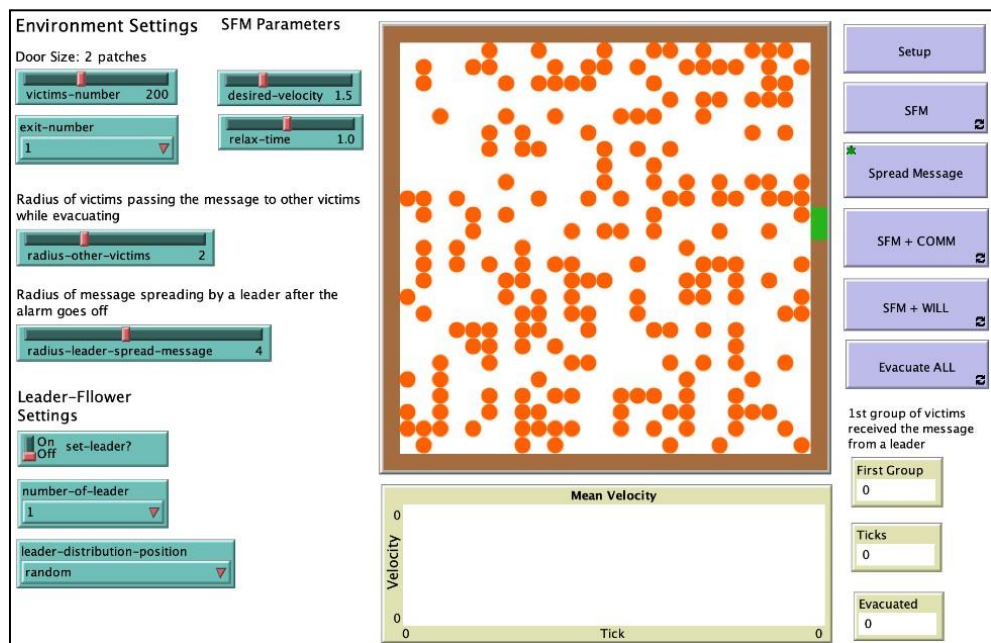


Figure 4.5: The NetLogo Interface For Room Evacuation

Figure 4.6 shows the code snippet of the NetLogo that describes the implementation of updating the knowledge value of the victim agent.

```
let walkable-path one-of neighbors with [ pcolor = white ]
if any? patches with [leaderPoint?] in-radius radius-leader-spread-message
[
  if walkable-path != nobody [ ask walkable-path [ set pcolor 119 ] ]
]

ask patches with [pcolor = 119]
[ ask victims-here [
  if victims-here != is-leader?
  [ set color pink
    set state 1
    set is-follower? true
    set groupstate 1
    set leader-update-knowledge-value 0.5
    set update-value knowledge-value + leader-update-knowledge-value
    set label update-value]
  ]
]
```

Figure 4.6: The NetLogo Code to Update the Knowledge Value of The Agent

Figure 4.7 shows the code snippet of the NetLogo that describes the implementation of group force within the agent. The group force is implemented to allow the follower agent to follow the leader towards the exit door.

```
ask pedsgrouping in-radius (1 * D) with [not (self = myself)
and knowledge-value < 1.5]
[
  set repvg
    repvg + will * A * exp((1 - distance myself) / D)
    * (k + sin(towards myself))
    * (k + (1 - cos(towards myself - h)))
  set repyg
    repyg + will * A * exp((1 - distance myself) / D)
    * (k + cos(towards myself))
    * (k + (1 - cos(towards myself - h)))
]

set speedx
  speedx + dt * (repvg + repx + (Desired-Velocity * sin hd - speedx)
/ Relaxation-Time)
set speedy
  speedy + dt * (repyg + repy + (Desired-Velocity * cos hd - speedy)
/ Relaxation-Time)
```

Figure 4.7: The Implementation of Group Force

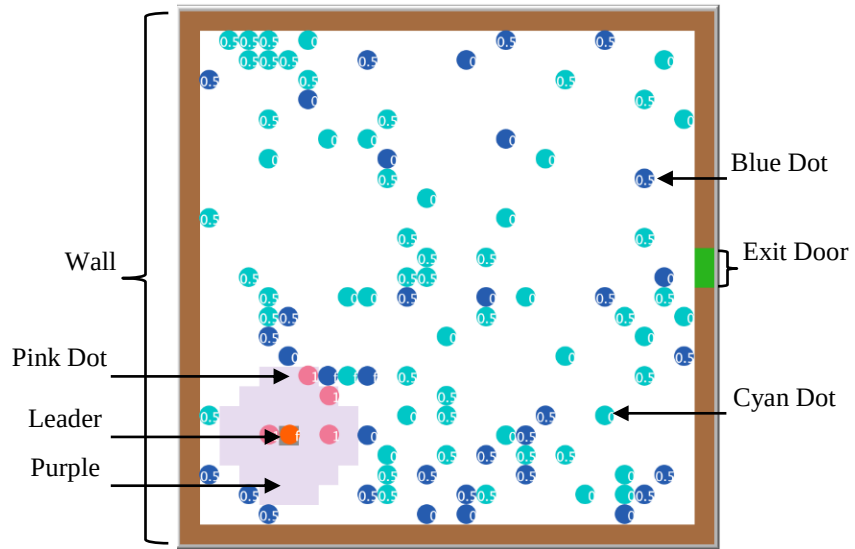
4.3.5 Simulation and Result Analysis

The simulation model was developed and ran for multiple series of evacuation experiments. The experiments were performed using laptop with Intel Core i5 3.1 GHz CPU with 8 GB RAM. The time for evacuation is measured using the NetLogo simulation unit named Tick.

The following figures present the stage in evacuation simulation that involves the spreading of the message by the leader, the formation of the group, the group evacuation, and the whole evacuation process.

Figure 4.8 presents the completed process of message spreading among the victim agents. The leader (represented by an orange circle) is sending or spreading message to his or her neighbour victims within a radius of 2. It is an interested to reported that that the white patches changes to purple, which indicates the area that a leader able to spread the message.

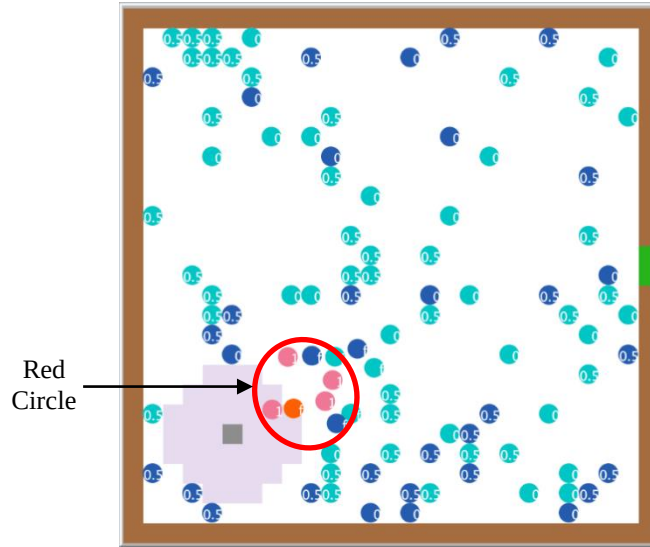
Figure 4.9 presents the movement of victim agents. Once the victim agents receive the message, they will start to move, following the leader towards the exit door. The group, denoted by the red circle, begins evacuating the room.



Legends:

Brown Line 	Wall/Static Obstacles
Green Line 	Exit Door
Blue Dots 	Victims with knowledge value of 0 and 0.5
Cyan Dots 	Victims with knowledge value of 0 and 0.5
Pink Dots 	Victims with knowledge value of 1.0
Orange Dots 	The leader
Purple Patches 	Range of message spreading

Figure 4.8: The Message Spreading During The Initial Simulation Run

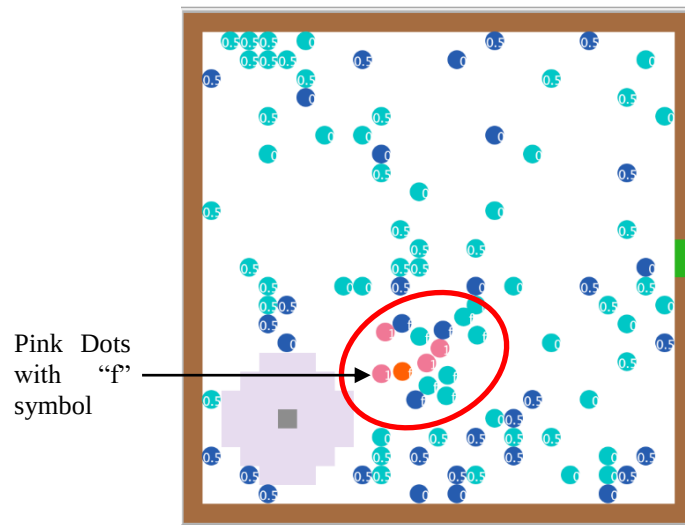


Legends:

Brown Line 	Wall/Static Obstacles
Green Line 	Exit Door
Blue Dots 	Victims with knowledge value of 0 and 0.5
Cyan Dots 	Victims with knowledge value of 0 and 0.5
Pink Dots 	Victims with knowledge value of 1.0
Orange Dots 	The leader
Purple Patches 	Range of message spreading
Red Circle	Groups of victim agent

Figure 4.9: The Victim Agent That Received The Message Starts Evacuating

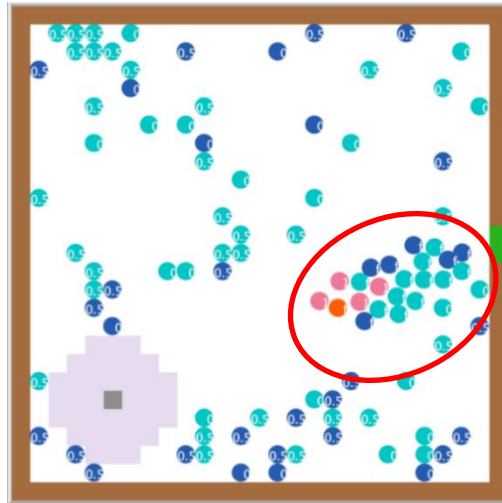
Figure 4.10 presents the passing of messages to neighbour victim agents throughout the evacuation process. While evacuating, the group of victims continue to pass the message to adjacent victims. The adjacent victims who became members of the group are denoted by the symbol 'f'.



Legends:

Brown Line 	Wall/Static Obstacles
Green Line 	Exit Door
Blue Dots 	Victims with knowledge value of 0 and 0.5
Cyan Dots 	Victims with knowledge value of 0 and 0.5
Pink Dots 	Victims with knowledge value of 1.0
Orange Dots 	The leader
Purple Patches 	Range of message spreading
Red Circle	Groups of victim agent
"f"	Follower agent

Figure 4.10: Passing Message To Neighbouring Victim Agents



Legends:

Brown Line 	Wall/Static Obstacles
Green Line 	Exit Door
Blue Dots 	Victims with knowledge value of 0 and 0.5
Cyan Dots 	Victims with knowledge value of 0 and 0.5
Pink Dots 	Victims with knowledge value of 1.0
Orange Dots 	The leader
Purple Patches 	Range of message spreading
Red Circle	Groups of victim agent
“f”	Follower agent

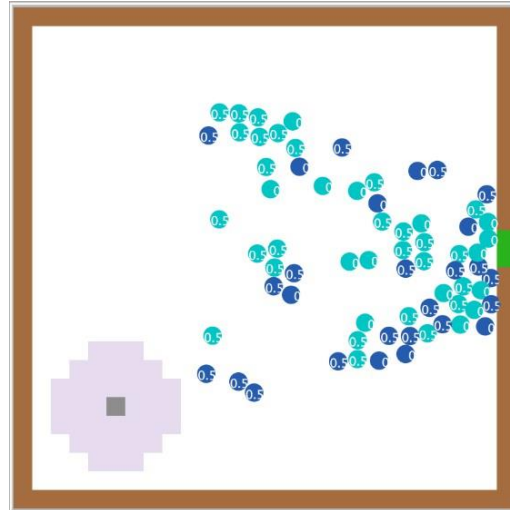
Figure 4.11: The Group Size Increased

In the simulation, when the message spreading is restricted to a 2-radius range, the transmission of information to distant victim agents such as those located in the far-end corners of a room is made possible through a relay-based word-of-mouth (WOM) mechanism. Rather than reaching all agents directly, the message propagates progressively from one informed agent to another within the designated radius. As each agent receives the message, they, in turn, act as intermediaries by transmitting the message to others nearby, thus creating a ripple effect across the agent population.

Additionally, as informed agents begin moving toward the designated exit, they serve as mobile carriers of the message, potentially encountering and informing other agents along their path. This dynamic, mobile spreading allows the message to eventually reach agents located farther away from the original source. However, this approach also introduces limitations. In sparse or fragmented populations, the lack of sufficient intermediary agents may interrupt the transmission chain, leaving some agents uninformed. Similarly, physical obstructions, if present in a more complex model, could hinder message flow. Moreover, agents positioned far from the leader may receive the message too late for effective evacuation. These observations suggest that while the WOM method supports gradual message propagation, future model enhancements could include more efficient awareness mechanisms, such as visual alerts or sound-based cues, to ensure more rapid and comprehensive communication during evacuation scenarios.

Figure 4.11 presents the changes in group size. The group is currently making their way out of the room. It is noted worthy that the message spreading has been performed successfully. Take note of the increased group size.

Figure 4.12 presents the movement of other victim agents towards the exit door. This occurred right after the first group of agents successfully evacuated the room.



Legends:

Brown Line 	Wall/Static Obstacles
Green Line 	Exit Door
Blue Dots 	Victims with knowledge value of 0 and 0.5
Cyan Dots 	Victims with knowledge value of 0 and 0.5
Pink Dots 	Victims with knowledge value of 1.0
Orange Dots 	The leader
Purple Patches 	Range of message spreading
“f”	Follower agent

Figure 4.12: The Other Victim Agents Start Evacuating the Room

Table 4.4 summarizes the evacuation ticks for each scenario when $DV = 1.0 \text{ ms}^{-1}$

¹. Note that N is the number of victim agents in the simulation, and DV is desired

velocity of agents, is set to 1.0 ms^{-1} . R1 is set to have radius of message passing to other victims =1, and radius of leader passing message = 2, while R2 is set as radius of message passing to other victims =2, and radius of leader passing message = 4.

Table 4.5 elaborates the evacuation ticks for each scenario when $DV = 1.5 \text{ ms}^{-1}$. Note that other parameter settings are same with the first experiments.

Table 4.4: The Evacuation Time in Ticks using $DV = 1.0 \text{ ms}^{-1}$

DV = 1.0 ms^{-1}	N = 100		N = 200		N = 300		N = 400		N = 500	
	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2
Victims per group	6	13	10	29	22	44	33	65	52	92
1st Phase Evacuees	25	49	57	162	136	295	313	400	490	500
Group Evacuation Ticks	776	968	1189	2365	2162	4116	4493	5556	6803	6928
Total Evacuation Ticks	1905	1850	3202	3174	4465	4657	5903	5556	7394	6928

Table 4.5: The Evacuation Time in Ticks using $DV = 1.5 \text{ ms}^{-1}$

DV = 1.5 ms^{-1}	N = 100		N = 200		N = 300		N = 400		N = 500	
	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2
Victims per group	7	14	12	26	19	44	31	62	54	87
1st Phase Evacuees	24	46	65	175	143	287	283	399	486	499
Group Evacuation Ticks	529	616	862	1635	1471	2568	2622	3510	4280	4354
Total Evacuation Ticks	1275	1204	2118	2081	2923	2857	3799	3626	4708	4543

Figure 4.13 shows the total evacuation times when DV is set to 1.0 ms^{-1} . Noted that total evacuation times are slightly higher when R2 settings are applied compared to R1. In R2, radius of message passing to other victims and radius of leader passing message are doubled to 2 and 4. The increased value in radius of spreading message concluded that the number of victim agents that formed a group and follow the leader is greater compared to R1 settings.

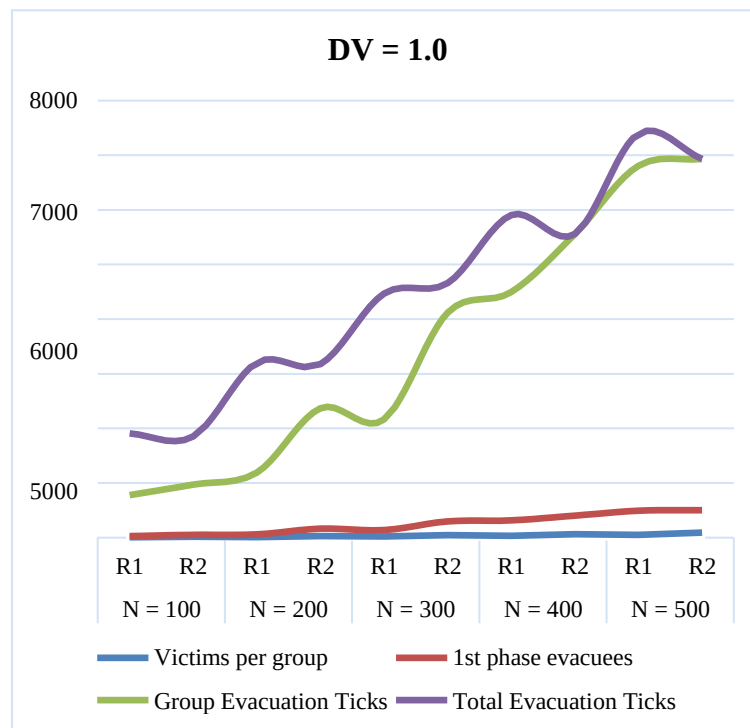


Figure 4.13: Total Evacuation Times For Simulation Scenario With $DV = 1.0 \text{ ms}^{-1}$

Figure 4.14 shows the total evacuation times when DV is set to 1.5 ms^{-1} . Note that total evacuation times are slightly higher when R2 settings are applied compared to R1. The simulation result presented in this scenario is almost the same as the result presented above. Note that the trend in increasing total evacuation time when R2 is

applied compared to R1 is somewhat closer to result we previously presented in Figure 4.13. However, the total evacuation time for this experiment is shorter compared to previous experiments.

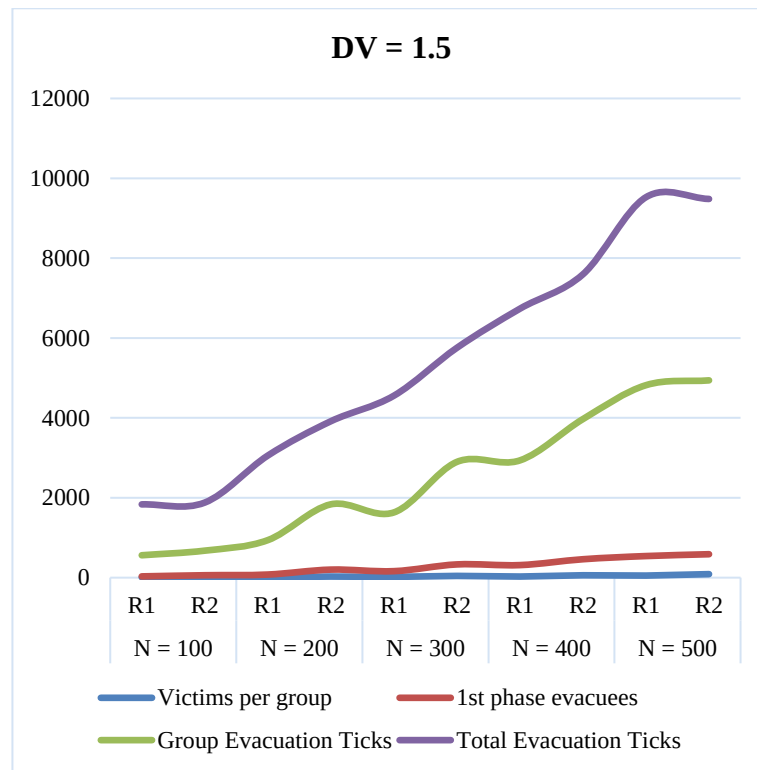


Figure 4.14: Total Evacuation Times For Simulation Scenario With $DV = 1.5 \text{ ms}^{-1}$

When R1 is changed to R2, the evacuation time decreases in both scenarios ($DV = 1.0$ and $DV = 1.5$). However, on a single instance, with $N = 300$ and $DV = 1.0$, the evacuation ticks rose somewhat by 4% when R1 was changed to R2. In the other scenarios, the reduction in evacuation ticks ranges from 1% to 6%.

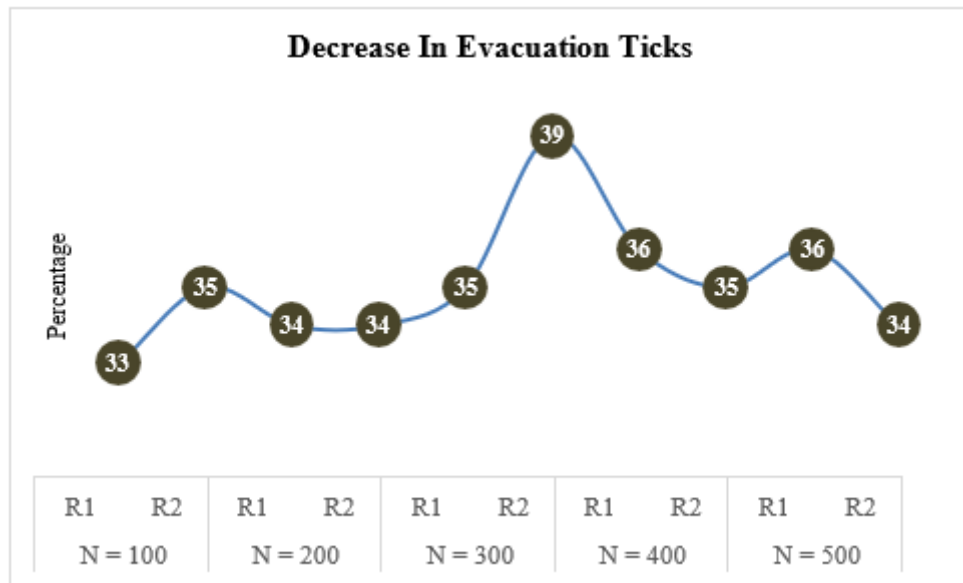


Figure 4.15: Total Decrease in Evacuation Ticks When DV is Increased From 1.0 to 1.5ms^{-1}

Figure 4.15 shows the percentage of evacuation ticks decreases as the DV is increased from 1.0 to 1.5ms^{-1} .

4.3.6 Simulation Comparison

In this section, we compare the simulation performed in this chapter with the message spreading in the previous simulation conducted in Chapter 3. The simulation experiments conducted in Chapter 3 involved the use of original SFM. In the comparison, we aim to analyse key factors that influence the accuracy, realism, and performance of each simulation. As shown in Figure 4.16, the evacuation ticks are compared between the experiment conducted without a group (e.g. SFM) that has been conducted in Chapter 3, and the experiment conducted with a group (e.g. SFM extension with communication model), both run with a single exit door. When grouping techniques

are used in conjunction with message passing, evacuation ticks increase by between 4% and 31%. When N equals 100, the proportion is fairly high: 28% for $DV = 1.0$ and 31% for $DV = 1.5$. However, from $N = 200$ to $N = 500$, the amount of increase drops.

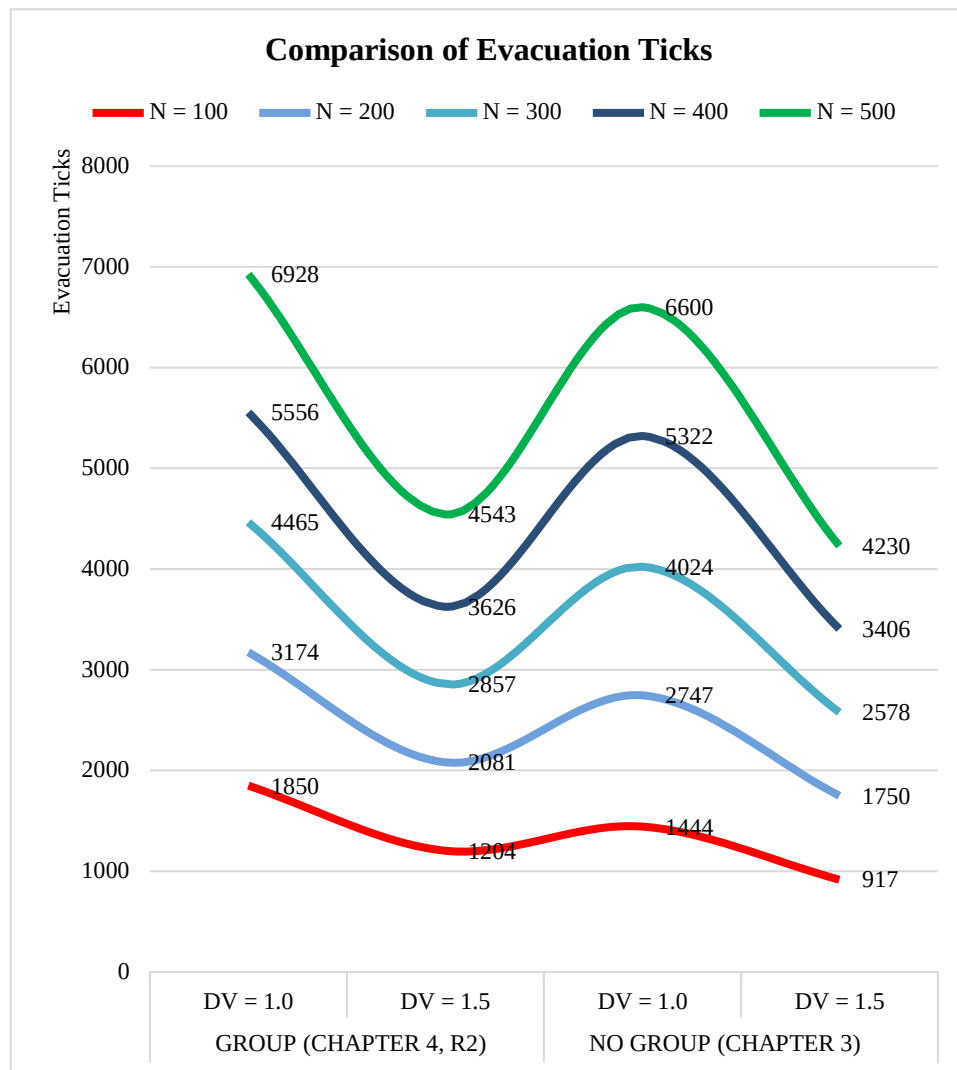


Figure 4.16: Comparison of Evacuation Ticks in Single Exit Experiments

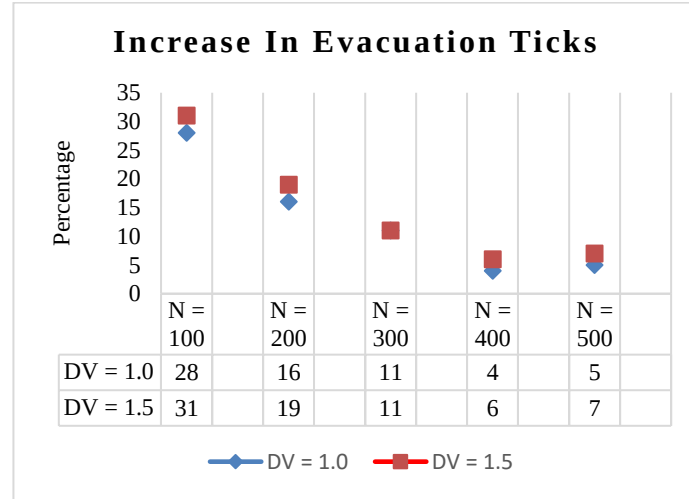


Figure 4.17: Comparison of Evacuation Ticks in Multiple Exits Experiment

According to Figure 4.17, the percentage of evacuation ticks increased when group approach and message passing were used. When the number of victim agents is 100 and DV equals 1.0, the evacuation differences between the experiment performed in Chapter 3 and in this chapter is about 28% increased. However, when the number of N is gradually increased, the difference in percentage is reduced. This is due to the size of the group formed during the evacuation. When N increases, the group size increases. Thus, the number of victim agents that move together at the same time towards the exit door increases.

Figure 4.18 shows the mean velocity for the experiment with and without the group using a single exit. Figure 4.18 (a) No group, DV = 1.0, N = 100, (b) No group, DV = 1.0, N = 200, (c) No group, DV = 1.5, N = 100, (d) No group, DV = 1.5, N = 200, (e) Group, DV = 1.0, N = 100, (f) Group, DV = 1.0, N = 200, (g) Group, DV = 1.5, N = 100, and (h) Group, DV = 1.5, N = 200. As illustrated in Figure 4.18, the mean velocity for the simulation using the group technique increased somewhat near the simulation's

completion. This is because the few remaining victims who are not part of the group have more space to walk, increasing their velocity. In all the graphs, the mean velocity climbed considerably during the initial evacuation before gradually decreasing. This is because the victims desired a certain velocity, but due to the proximity of other victims, they were forced to reduce their walking velocity.

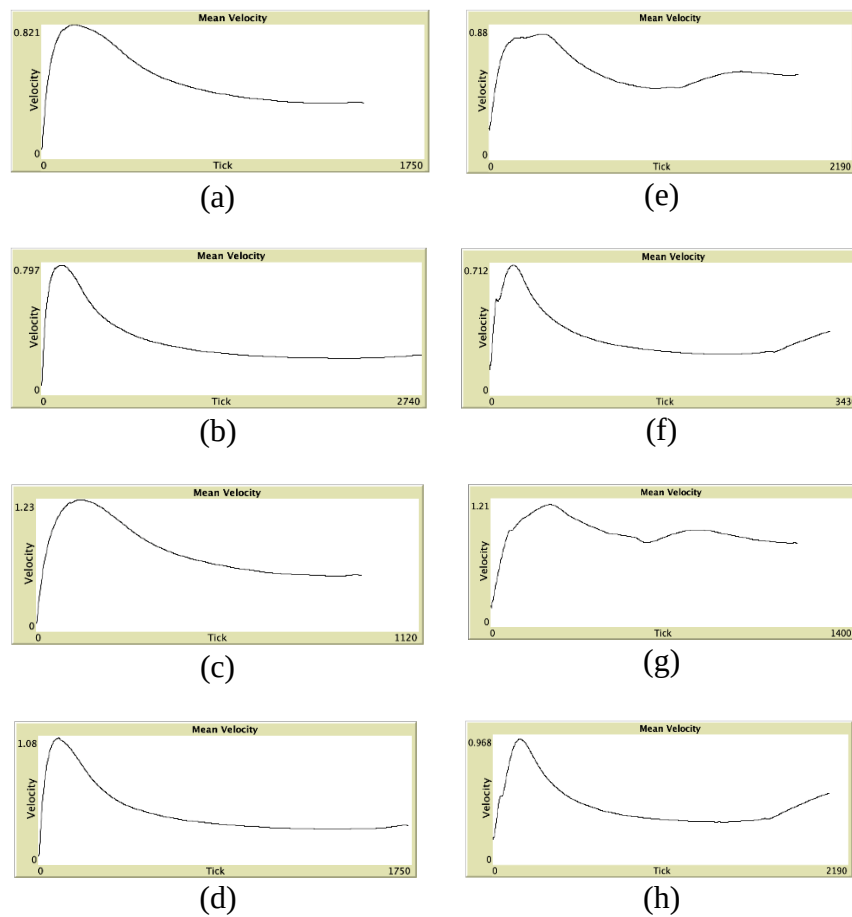


Figure 4.18: The Mean Velocity For The Simulation Experiment With And Without Group

The comparison of the simulation results achieved in the experiments conducted in Chapter 3 and Chapter 4 are simplified the following table. According to Table 4.6, both experiments involved evacuating 100 people from a 158.7m^2 room (25x25 patches, 1 room),

with one exit of 0.6m width and no fire, normal visibility. The key difference is in the behaviour modelled. Chapter 4 includes three types of agents with varying knowledge levels and Chapter 3 does not specify agent behaviour. As a result, Chapter 3's evacuation is faster, taking 917 ticks, while Chapter 4 takes 1204 ticks which is 287 ticks longer. The increasing ticks is likely due to the added behavioural complexity.

Table 4.6: Evacuation Simulation Comparison

Parameter	Experiment in Chapter 4	Experiment in Chapter 3
Number of People	100	100
Room Size (m²)	158.7	158.7
Room Layout	25x25 patches, 1 room	25x25 patches, 1 room
Number of Exits	1	1
Exit Width	0.6m per exit	0.6m per exit
Total Exit Width (m)	0.6	0.6
Agent Walking Speed	1.5ms ⁻¹	1.5ms ⁻¹
Evacuation Time (Tick)	1204	917
Behaviour Modelled	Has three types of agents (building personnel, frequent visitor, rare visitor) with different value of knowledge level	No specific behaviour
Assumptions / Notes	Normal visibility, No fire on sight	Normal visibility, No fire on sight

The key reason of the slightly increased evacuation time in Chapter 4 is the behavioural complexity introduced. The three types of agents are building personnel, frequent visitor, and rare visitor has different familiarity with the exits. Building personnel likely have high familiarity with exit door, frequent visitors have moderate familiarity and rare visitors have low familiarity or uncertainty. In contrast, in Chapter 3, all agents behave uniformly, likely heading directly to the exit using the shortest path. There is no decision-making delays or varied knowledge levels. This results in faster evacuation, even though room size, exit width, and speed are the same.

4.4 Discussion

This chapter proposes a building evacuation simulation using the SFM integrated with the communication model. The communication model demonstrates the WOM method of spreading the message during the evacuation process. The WOM is used to simulate how information spreads among people during evacuation. When one agent (person) becomes aware of the evacuation (e.g., hears an alarm or sees others running), they can spread that information to nearby agents. As a result, agents who receive the message tend to form a group and follow a leader (an informed agent) toward the exit. This simulates real-world behaviour, where people often follow others who seem confident or familiar with the route.

When the WOM is initiated, the victim agent forms a group to follow the leader exiting the room. Grouping techniques are used in conjunction with message passing; evacuation ticks increase by between 4% and 31%. This is because the few remaining victims who are not part of the group have more space to walk, thus increasing their velocity. Once agents are grouped and following a leader, grouping behaviour changes

the crowd dynamics. The evacuation time increased by 4% to 31% because grouped agents move more closely together, often waiting for others or sticking to the group. However, a small number of ungrouped agents (those who did not receive the WOM message) are left to evacuate independently. These ungrouped agents face less congestion, so they can move faster and increase their own velocity. Overall, for all the simulation scenarios, the mean velocity climbed considerably during the initial evacuation before gradually decreasing. The mean velocity increased at the start due to reason when the agents begin moving quickly, especially those who are ungrouped or first to react. The mean velocity was then gradually decreased as more agents form groups and the crowd density rises near the exit door, movement slows down due to congestion and coordination among group members.

Based on the simulation results in this chapter, which integrated the SFM with an agent messaging model and observed grouping behaviour affecting evacuation dynamics, there are several meaningful directions that we can expand the findings. The findings can be expanded to explore the role of communication dynamics further. We can simulate different levels of message spread such as fast, delayed, or incomplete communication to analyse the effect of varying the effectiveness of WOM. Other than that, we can study the effect of false or conflicting message during evacuation such as misinformation or panic-driven rumours. The findings can also be expanded by simulating the agents using the more complex layouts such as multi-room buildings, staircases, or high-rise layouts. Moreover, we can perform the sensitivity analysis to analyse how evacuation time changes with different exit widths, various groups sizes and varying agent densities. The findings from the sensitivity analysis can be used to

identify critical thresholds where communication becomes most helpful or harmful. The findings in this chapter can be compared with the real-world of experimental data. We can calibrate the SFM and WOM model using observed human behaviours in real-life emergencies. We also can expand the findings by introducing the stress levels or emotional states into agents to simulate how panic might affect communication efficiency, group cohesion, and movement speed. Hazard also can be incorporated to limit visibility or block the paths to study how communication and grouping adapt when routes are suddenly unavailable.

4.4 Threat Validation

According to the simulation approach and findings, there are some limitations that may affect the results, realism, or generalisability of the study. The limitations are highlighted in the following table.

While Chapter 4 provides valuable insight into how communication and behaviour affect evacuation, the limitations include simplified environments, uniform agent behaviour, and idealised conditions. Real-world complexity such as panic, poor visibility, diverse agents, and obstacles are not fully represented, which may lead to underestimated evacuation time and oversimplified conclusions.

Table 4.7: Limitations of Findings in Chapter 4

Limitations	Descriptions
Simplified Physical Environment	• The simulation uses a basic room layout (25×25 patches, single room) with one or two exits. • Real buildings often have hallways, obstacles, multiple floors, or visibility constraints, which are not represented. • This simplification may limit the applicability of the results to complex environments such as malls, schools, or hospitals.
Uniform Agent Walking Speed	• All agents are assumed to walk at 1.5 m/s, which does not reflect real crowd variation. • In real scenarios, people walk at different speeds depending on age, physical condition, urgency, or panic. • This assumption may oversimplify flow dynamics and interaction effects in dense evacuations.
Ideal Visibility and Calm Conditions	• The simulation assumes normal visibility and no fire or smoke, which does not reflect emergency conditions. • Visibility impairment and fear can significantly alter movement speed, path selection, and decision-making. • Therefore, the results may underestimate real-world evacuation time under stressful or hazardous conditions.
Limited Communication Model Scope	• The WOM (Word-of-Mouth) model assumes message spreading is always effective and positively influences grouping.

Table 4.7: continued

	• In reality, communication can be incomplete, delayed, misleading, or even cause panic. • The model does not account for noise, confusion, or conflicting information.
Predefined and Static Group Behaviour	• The simulation defines agent types (building personnel, frequent visitors, rare visitors) with fixed knowledge levels. • In real situations, group formation is dynamic and influenced by social bonds, perception, and stress levels. • The fixed behaviour model may overlook adaptive or irrational decisions made during panic.
No Consideration of Agent Collision or Trampling	• While SFM does model physical repulsion between agents, extreme crowd pressure, trampling, or falling risks are not captured. • These are critical in high-density evacuations and can drastically affect safety outcomes.
Model Validation is Limited	• The model outcomes are not validated with real-world evacuation drills, empirical data, or benchmark models. • This affects the credibility and generalizability of the simulation findings.

4.5 Chapter Summary

This chapter presents how to simulate a mobile crowd steering system through the proposed agent crowd steering simulation model. In this model, the spreading of the message is performed by the leader and the victim agent, who is categorised as a frequent visitor. As explained in the previous chapter, the agent role is assigned to the victim agent according to the knowledge value derived by adding the pre-assigned knowledge value and updated knowledge value. When a hazard is found in the building, the central system will send a message to all victim agents informing them about the situation. The victim agent will communicate with the other victim agent (referring to those who have a knowledge value of 1 or more) while heading to the nearest exit door. The victim agent will be informed by the central system during the emergency about the status of the situation and whether they need to evacuate during the disaster. The leader then transfers the route information to the followers, during which they are instructed to follow the leader's instructions on the evacuation of the building.

In this chapter, the SFM integration with the communication model able to simulate the message spreading in guiding users during evacuation. The simulation results able to identify the effect of having different types of agents with varying knowledge level which added more realism to the simulation. The findings in the experiments from this chapter open doors to studying how information sharing and social behaviours affect the evacuation. The experiment can be expanded by increasing realism (e.g., complex layouts, stress level, obstacles), deepening analysis (e.g., group size, timing, behaviour types, and applying the model in real-world or policy contexts.

In summary, this chapter has demonstrated the capability of the proposed agent crowd steering simulation model in representing a mobile crowd evacuation system, where message dissemination is driven by both leader agents and knowledgeable victim agents. Through the integration of the Social Force Model with a communication mechanism, the simulation successfully illustrated how information is spread and how agents respond based on their roles and knowledge levels. These findings highlight the importance of role assignment and inter-agent communication in shaping evacuation dynamics. Building upon this, the next chapter (Chapter 5) will delve deeper into the behavioural dimension of the simulation by introducing the willingness parameter and examining leader-following behaviour. This extension aims to enhance the realism of the model by incorporating the variability in agents' decisions to follow guidance based on social influence and individual disposition, ultimately contributing to a more comprehensive understanding of human behaviour during evacuation scenarios.

CHAPTER 5

THE WILLINGNESS OF AGENT AND LEADER-FOLLOWING BEHAVIOUR

5.1 Introduction

In the previous chapter (Chapter 4), we presented the agent messaging model. We described how agent communicates with other agents during the evacuation process. This chapter presents the extension of previous development using the willingness of agents and leader-follower behaviour.

The section 5.2 presents the emergent behaviour that occurs during the evacuation. The section 5.3 explains the willingness parameter that we use in the experiment. Section 5.4 describes the group evacuation, Section 5.5 presents the simulation of the room evacuation, and finally, Section 5.6 explains the discussion of this chapter while Section 5.7 describes the threat validation for the experiments conducted. Finally, Section 5.8 summarises the chapter.

5.2 The Emergent Behaviour

The emergent behaviours arise during panic situations caused by the increased desired velocity of people who are trying to exit the building immediately (Stroehle, 2020). Emergent behaviour manifests throughout the process of evacuation due to a multitude of factors, predominantly arising from the complex interactions between individuals, their surroundings, and the specific conditions surrounding the evacuation. Emergency evacuation can give rise to several emergent phenomena, such as crowd flow patterns, herding behaviour, arching behaviour, emerging leadership, stress contagion, and spontaneous aid. The term "arching behaviour" pertains to a phenomenon

observed in emergency evacuation or crowd dynamics, wherein individuals or groups exhibit the formation of arch-like structures within a crowd. This behaviour commonly arises when there is a barrier or obstacle that obstructs the movement of individuals, such as a narrow entrance, a collapsed structure, or a congested area.

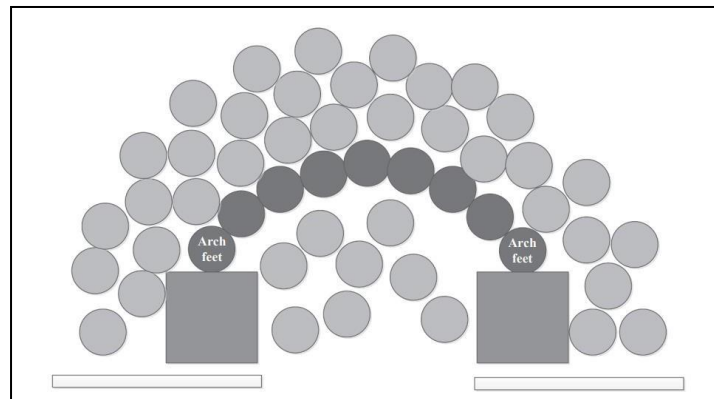


Figure 5.1: Arching Phenomena at the Exit Door (Li et al., 2019)

Although arching behaviour might serve as a valuable strategy for crowd control, it is crucial to acknowledge that it can also provide potential hazards, especially in cases where the structure becomes unstable or when individuals within the arch experience under pressure. Hence, it is imperative for emergency responders and crowd managers to possess knowledge regarding arching behaviour and to implement suitable strategies to safeguard the well-being of all those engaged in the evacuation procedure.

Herding phenomena occur during panic situations caused by the inability of people to react to the situation on their own. Hence, they tend to follow other people nearby during the evacuation. People made assumptions that other people were using the correct path to exit the door. When this situation occurs, we can see more people are using the same path leading to a particular exit door compared to other paths available.

Also known as leader-following behaviour, leader-following is one of the collective behaviours during emergency evacuation. In real human situations, when in a panic situation, people have a tendency to follow other people (Albi et al., 2021). The people who have the knowledge or information regarding the building layout are called leaders. The optimised leader has information about the position of the exit door (Albi et al., 2021). In some cases, the simulation has been done when the single leader is positioned at the centre of the room and group. (Turgut and Bozzdag, 2020).

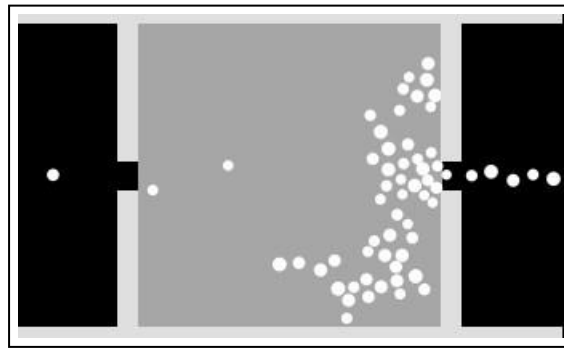


Figure 5.2: Herding Behaviour (Helbing et al., 2000)

5.3 The Willingness Parameter

The willingness parameter has been used for many purposes in crowd simulation studies, such as to model an agent's willingness to follow the leader (Zhou et al., 2019; Yanget al., 2014) and to help other agents during the evacuation process (Niu et al., 2015).

Willingness is one type of victim agents' behaviour that emerged during the evacuation process. In this research, we define the term willingness as the agent's willingness to follow the evacuation instruction received from the group leader, thus

evacuating a group of victims. If an agent has the willingness value, then the agent will look for the nearest leader, form a group, wait for the leader's instruction, evacuate the building by moving within a group, and finally decide whether to share the message with the other agents or not. The victim agent decides to follow a leader when the degree of willingness is equal to 1 or more than 1. The efficacy and results of the evacuation process can be strongly impacted by the level of cooperation, adherence to instructions, and implementation of suitable actions exhibited by these victim agents.

The computation of the willingness parameter is incorporated into the movement module of our proposed agent crowd steering simulation model for simulating crowd evacuation. This parameter gives the agent the ability to make decisions regarding whether to follow the leader's instructions and evacuate by following the leader's heading towards the exit door.

Figure 5.3 depicts how a victim agent decides whether to become a follower or leader. The victim agent will decide to become a follower or independent agent according to the value of willingness they possess.

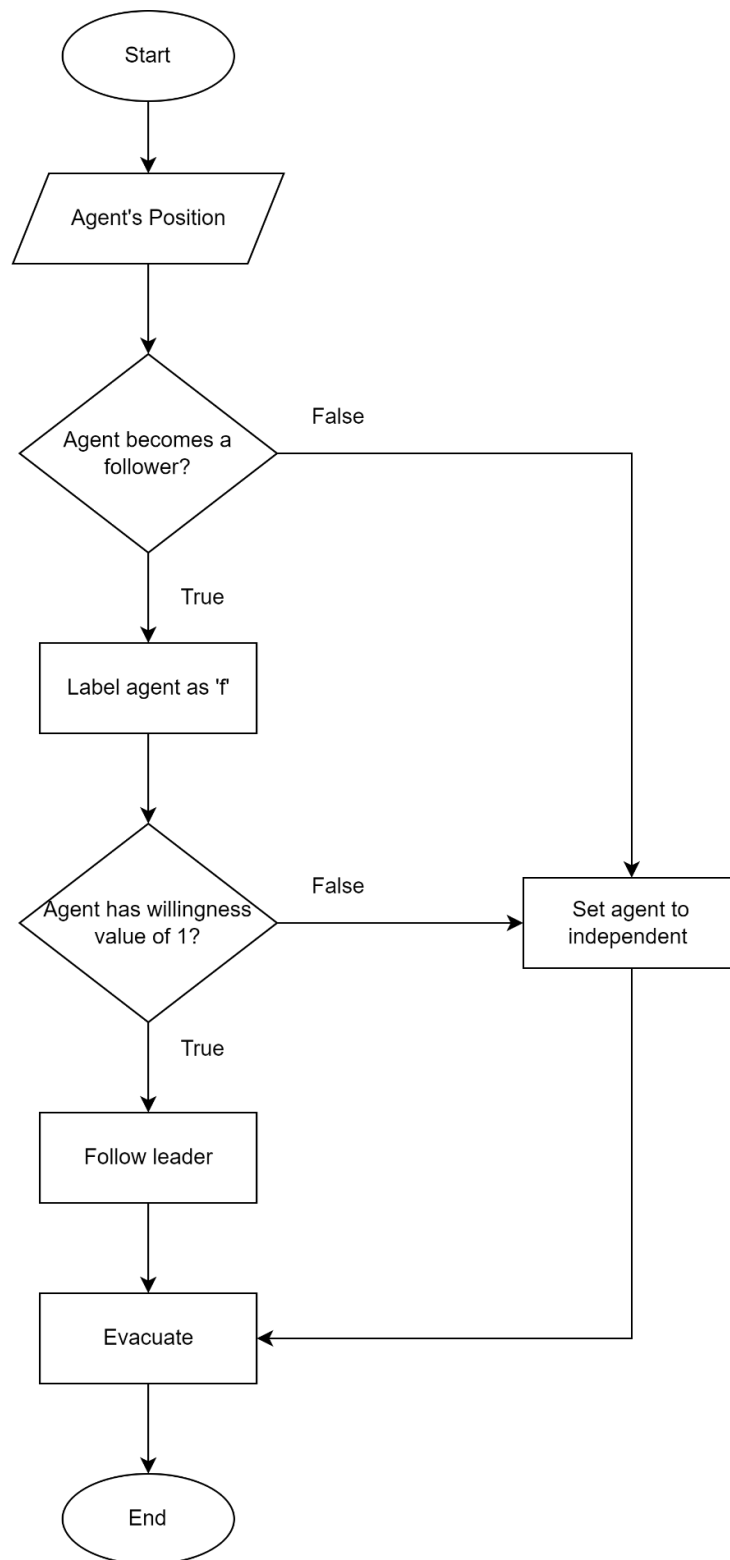


Figure 5.3: Deliberation Process of A Victim Agent Based Before Evacuating the Room

5.4 Group Evacuation

The level of cooperation, adherence to instructions, and mutual support exhibited by victim agents during the evacuation process is of utmost importance in group evacuation situations. The collective willingness of victim agents and the eventual success of the evacuation effort are influenced by a combination of group dynamics, leadership, communication, and peer influence.

The dynamics between leaders and followers are of utmost importance in influencing the processes of group evacuation. Efficient leadership encourages coordination, the exchange of information, mutual assistance, and flexible reaction to obstacles, finally increasing the overall safety and success of the evacuation effort.

The term "group evacuation" refers to the practice of fleeing a building as a group to reach the same exit door at the same time. It is expected that each group will be headed by a leader who knows how to get to the exit door, has easy access to evacuation information, and is well-versed in the facility's emergency procedures. The simulation of a crowd benefits from the realism provided by grouping as one of the realistic behaviours of the crowd. Realism is essential to the performance of crowd simulations.

The performance of a group evacuation in terms of evacuation time is influenced by several factors. This includes the size of the group, the interaction between members, the number of leaders, and the position of the leaders.

The size of the group refers to the number of people within a group that move together to reach their destination or exit door. Elzie et al. (2016) found that crowd density and evacuation duration are strongly influenced by the size of the average group.

The group's ability to evacuate is also influenced by the closeness of its members. To categorise the characteristic of people within a group, social relationship such as family, friends and co-workers will be assigned to the same group of people. These social relationships are influenced the decision-making process during evacuation (Haghani et al.,2019).

The amount of time for evacuations is also influenced by the social dynamics within a given social group. Several studies have also examined the correlation between the overall duration of evacuation and a leader's position. The formation of significant connections between individuals can be related to their shared social features. There exist several methods, among which the utilisation of social relationship value is employed to ascertain the degree of proximity between individuals (Liu et al., 2018).

The term "number of leaders" describes the ideal number of leaders required for a certain number of victims and room capacity. The study conducted by Hou et al. (2014) examined the necessary number of leaders in a building during an evacuation process. Based on their research, the leader's role is more significant than the number of leaders in determining the overall duration of the evacuation. Nevertheless, when the dimensions of a room or building increase, the quantity of leaders required for the evacuation also increases.

Our study examines the impact of many leaders present in a room during an evacuation. The leaders are situated in a predetermined coordinate system that establishes a fixed gap between them. The application of relationships in the simulation pertains to the knowledge value possessed by the victim and their proximity to the leader.

5.5 Simulating The Room Evacuation

In this simulation experiment, the model is built based on the following assumptions:

- i. There is no visible fire or smoke in the room.
- ii. Every victim agent will evacuate the room when the alarm goes off.
- iii. Victim agents can choose to use any exit door.

During the scenario, each victim agent will promptly escape the room when the alarm is triggered. In contrast, the simulation does not exhibit any visual representation of smoke or fire. The victim agents have the ability to utilize any accessible exit door. The simulation does not exhibit any observable obstruction.

5.5.1 Agent's Settings

For both experiments, the agent's settings are described as in Table 5.1. In these experiments, we designed the victim agents as having the roles of leader and follower. Both agents' roles have distinguished physical appearances to categorise them. Leader agent will be depicted in orange colour, while follower agent will be in pink colour, and both agents have the round shape.

Table 5.1: Agent's Settings

Characteristics	Victim Agents	
Role	Leader	Follower
Physical appearance:	Victim Agents	
1) Colour	Orange	Pink
2) Shape	Round	Round

Table 5.1: continued

Willingness type:	Victim Agents	
1) To form a group	1	0 or 1
2) To follow leader	0	0 or 1
3) To spread message	1	0 or 1
Knowledge value	1 and above	Less than 1

5.5.2 Experiment Settings

The experiments are designed to investigate three aspects: 1) the relationship between the degree of willingness and total evacuation time, 2) the relationship between the variation of willingness value and total evacuation time, and 3) the relationship between the number of leaders and total evacuation time. The room layout for the experiment is identical to the previous experiments.

5.5.3 Parameter Settings

The specification for the SFM models followed the work done by Helbing et al. (2000). Under panic conditions, the velocity (desired speed) of people leaving the room could increase from 1 to 1.5 ms^{-1} . The following Table 5.2 summarises the settings for the parameters used in this experiment.

Table 5.2: The Parameters Settings Used in The Experiments

Types of Parameters	Parameters	Settings	Remark
SFM Parameters	Constant A (Repulsive Strength)	1.0	Determines the strength of the repulsive force between pedestrians. The value 1.0 is optimum to avoid agents standing too close to each other (agents overlap). Higher value will move agents far from each other.
	Constant B (Repulsive Range)	0.5	Affect the range or distance over which the repulsive force acts. The value is optimum to avoid agents standing too far from each other.
	Relaxation Time	1.0	Refers to the time it takes for a pedestrian to adjust their speed and direction in response to the social forces acting upon them. Typical values are 0.5 – 1.0s.
	Desired Velocity	1, 1.5, 2.0	Represents the speed and direction an individual pedestrian aims to move towards their intended destination, independent of other people and obstacles. Typical values are 1.2 – 1.5 ms⁻¹ for normal situation. 1.5 above is set for high-stress situation.
	Derivative Time	0.05	The time derivative is numerically integrated using small steps such as 0.01s, 0.05s, or 0.1s. The value 0.05 generate more precise and slower simulation but smoother motion.
	Number of Victims	100, 200	The number agents are set to be between 100 and 200.

Table 5.2: continued

Willingness Parameters	Willingness to follow a leader	0, 1	The value 0 represents no willingness. The value 1 represents having willingness.
	Radius of message spreading	1, 2, 3, 4, 5	Radius of message spreading is set to be between 1 and 5.

It is noted that the desired velocity (DV) is set to three values (1.0, 1.5, and 2.0 ms^{-1}). The number of victims (N) is set to 100 and 200, while the radius of message spreading has five values, from 1 to 5.

5.5.4 Simulation and Result Analysis

The simulation was developed, and the experiments were performed using the laptop with Intel Core i5 3.1 GHz CPU and 8 GB RAM specification. Our simulation platform used the NetLogo simulation tool. The total evacuation time is measured using a tick number, which is the simulation time unit used in NetLogo.

Figure 5.4 illustrates the simulation scene, whereby three leaders are represented by circles of yellow and orange colour. The leaders are situated at a predetermined distance from one another. The fixed space between them determines the number of group members a leader will have. The leader is designated as "1" to symbolize the level of knowledge that they possess. All victim agents with a knowledge value of 1 will be designated as leaders in this study.

The simulated setting depicted in Figure 5.5 illustrates the process of message dissemination. The spread of the message is depicted by patches exhibiting a bright pink

and purple colour. The leader's position will also dictate the extent of message dissemination that is observable in the simulated scene. It has been observed that the leader in the top left is situated slightly towards the upper left corner of the room. Consequently, the leader possesses a distinct or limited range for disseminating their message, in contrast to the leader positioned at the lower left corner of the room. Within the simulation scene, it is depicted that the group member undergoes a colour shift to signify their successful integration into the group and subsequent adoption as a follower.

The evacuation process has been depicted in Figure 5.6. Victim agents will proceed to leave alongside their other group members by utilising the exit door that is closest in proximity. Nevertheless, while progressing towards the exit door, any member of the group has the ability to disseminate the message to a nearby victim agent, so encouraging them to join them and collectively go towards the exit door. It has been observed that the blue circle agents have been labelled as "f", but the physical colour remains the same. This is due to their exclusion from the group.

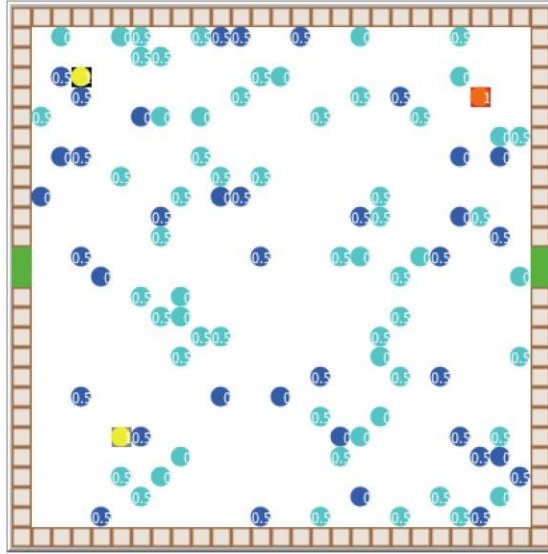


Figure 5.4: The Simulation Scene With Three Leaders

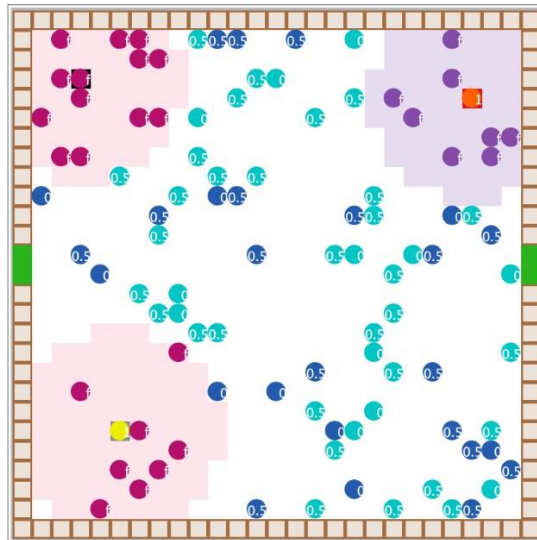


Figure 5.5: The Simulation Scene With Message Spreading Process

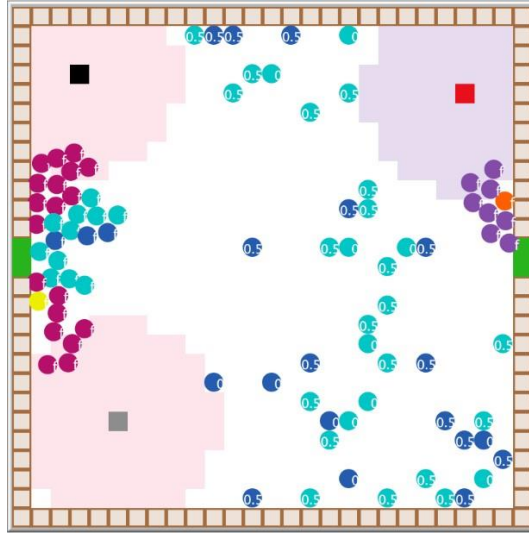


Figure 5.6: The Simulation Scene Shows the Victims Within the Group Evacuating

Table 5.3 summarizes the evacuation time for both experiments A and B. In these experiments, we set the number of victim agents (N) to be either 100 or 200. Note that N is the number of victim agents in the simulation, T is the simulation unit time, and DV is the desired velocity. Experiment A is conducted by introducing the willingness parameter, while experiment B has no willingness parameter.

Table 5.3: Evacuation Times For Experiment A And B

	Experiment A	Experiment B
Willingness	1	0
DV	1.0	1.0
N = 100	528	682
N = 200	1316	1371

According to Table 5.3, the evacuation times for experiment A are lesser than experiment B. We simplify the difference in the following graph. Figure 5.7 shows the interface design of the NetLogo for this simulation experiment.

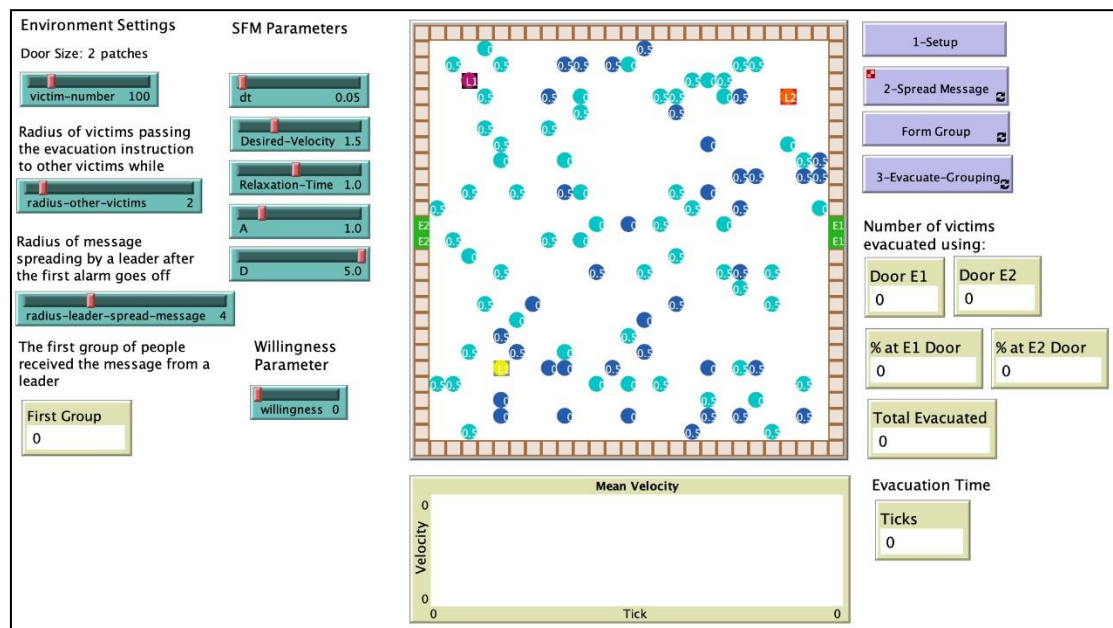


Figure 5.7: The Simulation Interface Design using NetLogo

The following is the code snippet that demonstrates the use of the willingness parameter in the agent crowd steering simulation model.

```

to choose-leader1

  ask max-n-of 1 victims [count victims in-radius 3]

  [

    move-to one-of patches with [pcolor = black and not any? turtles-here]

    set leader-radius-area patches in-radius 2

    set is-leader? true

    set color magenta

    set state 1

    set groupstate 1

    set knowledge-value 1

    set label knowledge-value

    set label "L1"

  ]

end

if any? patches with [pcolor = black] in-radius radius-leader-spread-message
[
  if walkable-path != nobody [
    ask walkable-path [ set pcolor 139 ]
  ]
]

```

Figure 5.8: The First Part of the NetLogo Code for The Implementation of the Willingness Parameter

```

ask patches with [pcolor = 139]

[ ask victims-here [
  if victims-here != is-leader?

  [ set color 125

    set state 1

    set is-follower? true

    set groupstate 2

    set leader-update-knowledge-value 0.5

    set update-value knowledge-value + leader-update-knowledge-value

    ;set label update-value

    set label "f"

  ] ] ]

ask turtles in-radius (2 * D) with [not (self = myself)]

[
  let wills willingness * 2;

  set repx repx + A * exp((1 - distance myself ) / D ) * (k + sin(towards myself ) *
( k + (1 - cos(towards myself - h)) + wills))

  set repy repy + A * exp((1 - distance myself ) / D ) * (k + cos(towards myself ) *
( k + (1 - cos(towards myself - h)) + wills) )

]

```

Figure 5.9: The Second Part of the NetLogo Code for The Implementation of the Willingness Parameter

```

set speedx

  speedx + dt * (repxg + repx + (Desired-Velocity * sin hd - speedx)

  / Relaxation-Time )

set speedy

  speedy + dt * (repyg + repy + (Desired-Velocity * cos hd - speedy)

  / Relaxation-Time )

]

```

Figure 5.10: The Second Part of the NetLogo Code for The Implementation of the Willingness Parameter

Figure 5.11 presents the evacuation times for scenario that using the willingness parameter and without willingness parameter. Note that the number of victim agents used in this simulation is 100 and 200.



Figure 5.11: The Evacuation Time Difference for Scenario with and Without Willingness Parameter

Evacuation ticks were reduced by 29.17 % for 100 agents and by 4.18 % for 200 agents when simulation used the willingness that equals 1. We found that increasing the number of agents in a simulation room decreases the effectiveness of employing the willingness parameter. This is because the number of agents who received the first-hand message is far larger than in a scenario where only 100 agents were involved. Figure 5.12 shows the number of victim agent evacuated captured at tick equals 500, 1000, 1500, and 2000, and the willingness parameter is set to 1. Noted that tick is the simulation unit used in NetLogo. It is clearly shown that the number of victim agents evacuated is larger for all ticks captured when N equals 200.

Figure 5.13 shows the number of victim agents evacuated captured at tick equals 500, 1000, 1500, and 2000, and the willingness parameter is set to 0. In this graph, the trend or pattern is almost the same as in the previous graph. There are only slight differences in the number of victim agents evacuated.

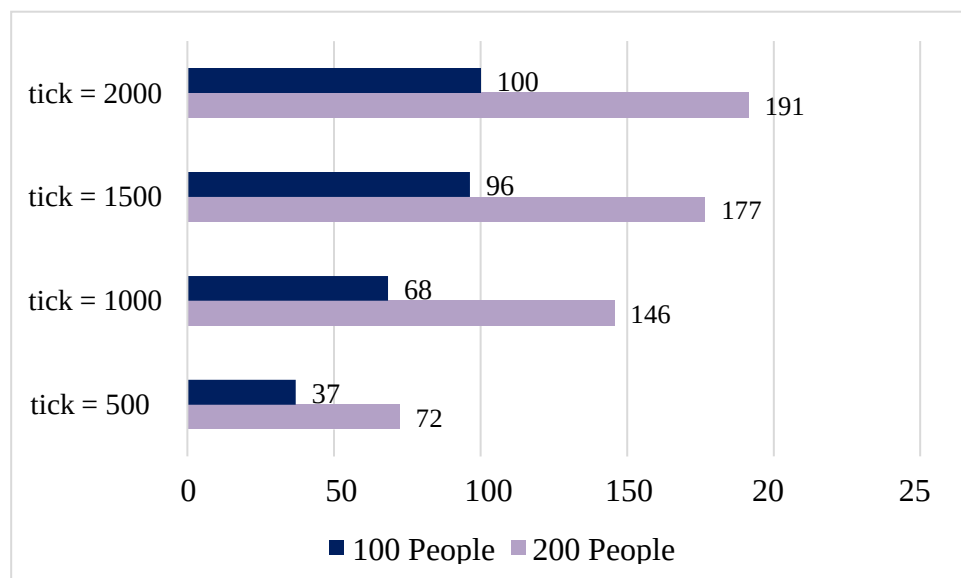


Figure 5.12: The Evacuation Time for Tick Equals To 500, 1000, 1500, 2000 and
Willingness = 1

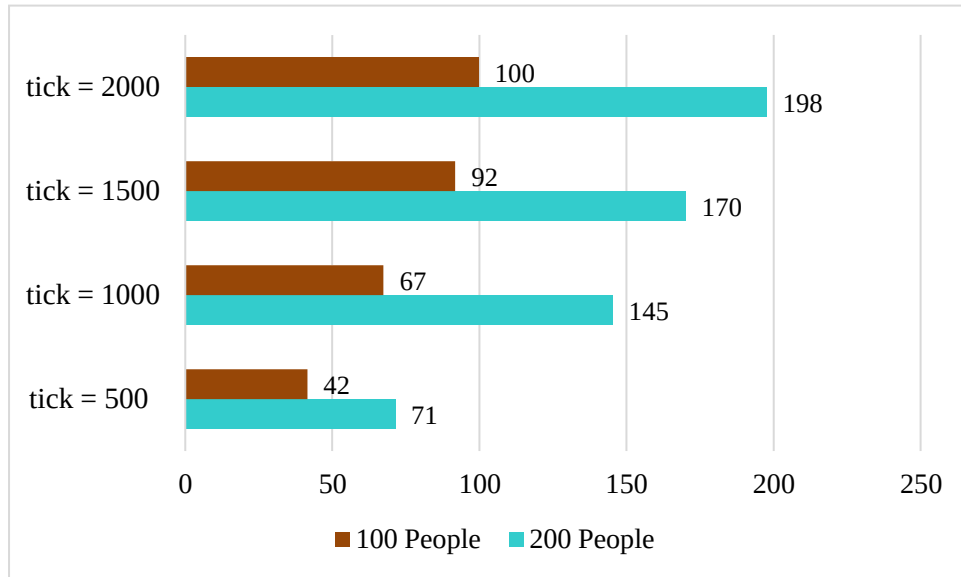


Figure 5.13: The Evacuation Time for Tick Equals To 500, 1000, 1500, 2000 and
Willingness = 0

As a further step, the simulation settings expand to three leaders. The difference in overall evacuation time for the scenario without the willingness parameter is shown in the following graph.

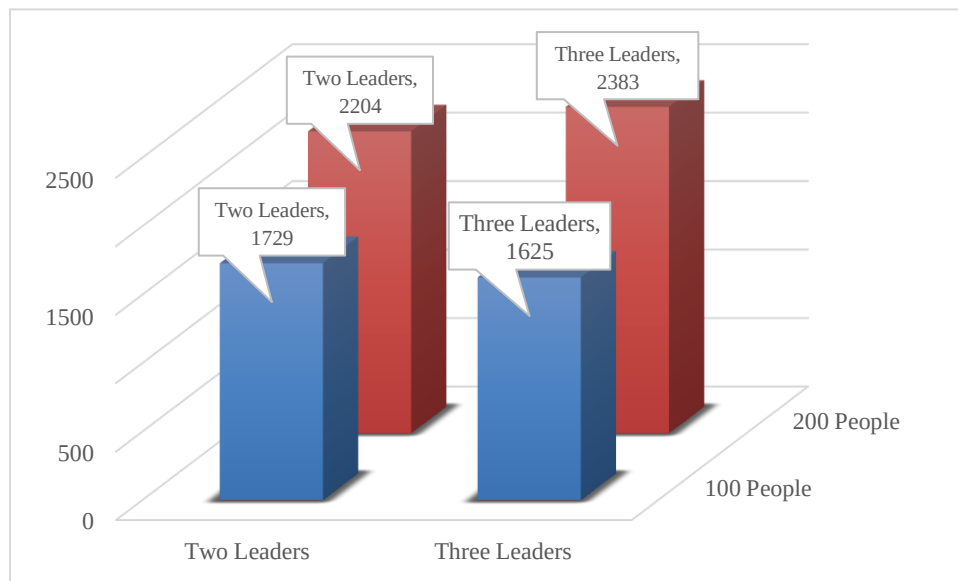


Figure 5.14: The Relationship Between the Number of Leaders and Total Evacuation Time With No Willingness Parameter

According to the simulation results, the evacuation duration is reduced by 6.02 % when the number of leaders is increased from two to three. However, the overall evacuation duration is increased by 15.51 % when three leaders are present. There was a substantial increase in the likelihood that all victims were given evacuation information at the same time if there were three simulation leaders present. As a result, a rising number of people are trying to evacuate and are making their way to the nearest exit.

The difference in total evacuation time caused by applying the willingness parameter is depicted in the graph that can be found below in Figure 5.14. When there are 100 people, the time it takes to evacuate the building increases by 2.20 %, while the time it takes for the simulation to complete is increased by 23.29 % with three leader and when there are 200 people participating. Meanwhile, the increased value when having two leader is 26.25 % when applying willingness parameters.

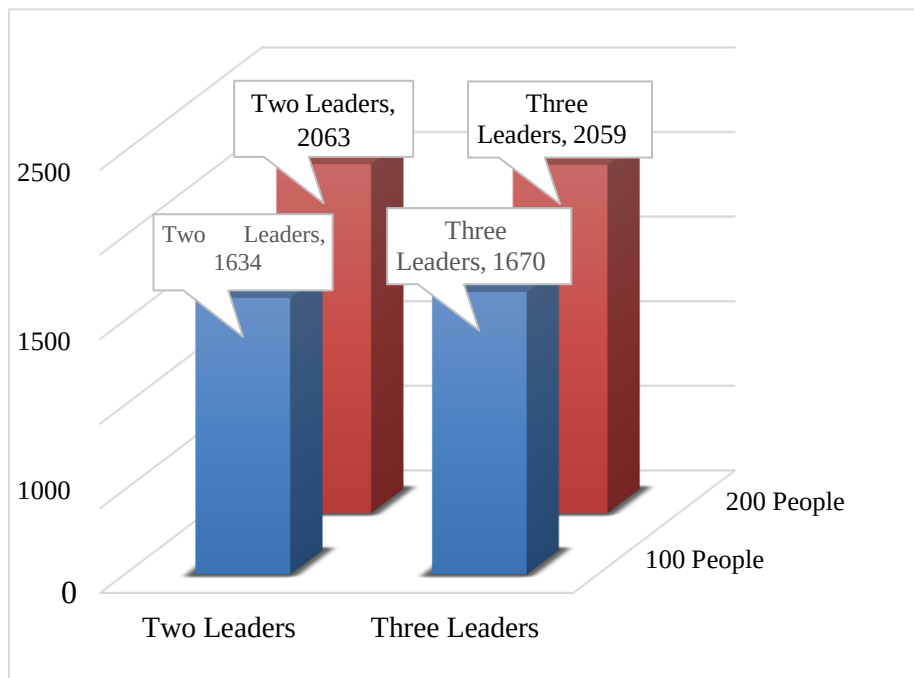


Figure 5.15: The Relationship Between the Number of Leaders and Total Evacuation Time With Willingness Parameter

5.5.5 Simulation Results Comparison

The simulation results gathered in this chapter will be compared to the one presented in Chapter 3. Note that the comparison is made only to the experiment that was using $DV = 1.0\text{ms}^{-1}$ and using multiple exit doors, which are two doors. N is the number of victim agents.

Table 5.4: Comparison in Evacuation Times

	Experiment in Chapter 3	Experiment in Chapter 5	
		Willingness = 0	Willingness = 1
N = 100	955	682	528
N = 200	1563	1371	1316

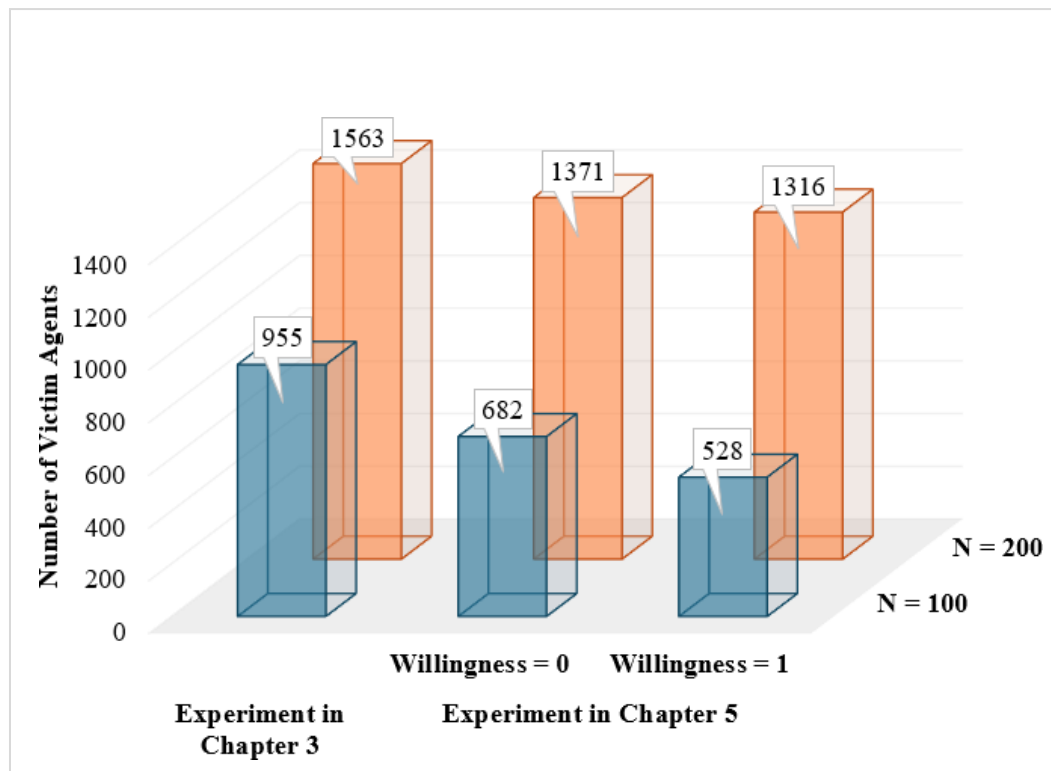


Figure 5.16: The Relationship Between the Number of Leaders and Total EvacuationTime with Willingness Parameter

Figure 5.16 shows the comparison of the results of the simulation experiment conducted in Chapter 3 and Chapter 5. In Chapter 3, the simulation experiment is performed by adopting the original SFM. In this chapter, the willingness parameter is added to the SFM, added spreading messaging capabilities to victim agents, and observed the results. For $N = 100$, willingness and DV are set to 0, and the total evacuation in a tick is reduced by 28.59%. For $N = 100$, and willingness is set to 1, compared to the experiment in Chapter 3, the evacuation time is reduced by 44.71%.

For $N = 200$, willingness and DV are set to 0, and the total evacuation in a tick is reduced by 12.28%. For $N = 200$, and willingness is set to 1, compared to the experiment in Chapter 3, the evacuation time is reduced by 15.80%.

Note that the average increased percentage of total evacuation time when N is increased from 100 to 200 is 104.6%. The observed increase in evacuation time at $N = 200$ can be attributed to the delay in evacuation resulting from the victim agent's allocation of time towards spreading the message to neighbouring victim agents.

The inclusion of the willingness parameter in the research is justified despite the seemingly insignificant reduction in evacuation time, because it offers valuable insights into realistic human behaviour dynamics during emergencies. Willingness represents an individual's internal motivation or decision to evacuate after receiving a message or perceiving a threat. In real-life situations, not everyone reacts immediately to an emergency; people vary in their response due to emotional state, perceived risk, or uncertainty. Therefore, incorporating willingness provides a more behaviourally accurate model of evacuation, rather than purely relying on physical movement or pathfinding.

Although the reduction in total evacuation time appears minimal in percentage terms, the parameter reveals critical group interaction patterns, such as delay in response, hesitation, or reluctance to act, which can influence congestion, group formation, and overall safety outcomes. Moreover, the simulation findings align with related studies (e.g., Ma et al., 2022), reinforcing the observation that an increase in willingness alone does not guarantee faster evacuation. In fact, under certain conditions, it may introduce delays due to social dynamics and coordination time.

Furthermore, willingness becomes significantly more relevant in complex or multi-room environments, where awareness is unevenly distributed and leadership is unclear. In such cases, even minor behavioural delays can lead to disproportionate consequences. Including willingness in the model also allows for future extensions, such as integrating awareness levels, emotional states, or social influence, making the model more adaptable for empirical studies or real-world planning.

In conclusion, the willingness parameter enriches the model by capturing human variability in decision-making, providing a foundation for more realistic and nuanced evacuation simulations, and enabling better-informed safety designs and evacuation protocols.

From the findings, we conclude that the integration of willingness and communication behaviour into the SFM affects evacuation outcomes significantly. While message spreading introduces delays (when $W = 0$), it becomes a strength when combined with high willingness, improving coordination and exit efficiency.

5.6 Discussion

The willingness parameter could reduce the total evacuation time given that the number of leaders is suitable for a specific room size and design. However, the reduced time is insignificant. The simulation results support the work done by Ma et al. (2022); when there is a growing number of people who are willing to evacuate, the circumstance will cause the overall evacuation period to be extended. Gray-Graves et al. (2011) found that for a 100% cooperative group, evacuation efficiency increases with emergency, and

uncertainty decreases with evacuation. The finding reveals that evacuation efficiency is low when evacuation information is adequate for crowds with low cooperation.

When employing a more complex architecture, such as having numerous rooms on a floor, the usefulness of using the willingness parameter will be clearly stated in a more precise manner. This is because of the wall, which prevents victims from seeing other victims nearby who may have started to evacuate after getting instructions.

The inclusion of the willingness parameter in the SFM allows agents to demonstrate varying levels of motivation or intention to evacuate once they receive a message. While this modification adds a layer of realism to evacuation behaviour, the findings suggest that the impact on overall evacuation time is limited, especially when the number of leaders (those who initiate evacuation) is not well optimised for the specific size and layout of the building.

Although simulations indicate that willingness can reduce evacuation time, the decrease is not significant unless a carefully balanced leader-to-follower ratio is used. Too few leaders may result in communication delays, while too many can lead to congestion near exits, negating the intended benefits.

While the willingness parameter shows potential to improve evacuation coordination, its effectiveness is highly context-dependent. In simple room layouts, the gains are minimal. However, in complex architectural spaces, willingness combined with strategic leader distribution and communication dynamics can significantly enhance evacuation outcomes.

The findings presented in Chapter 5 demonstrate several advancements over those in Chapter 4, particularly in terms of behavioural realism and evacuation efficiency. While Chapter 4 introduced diverse agent profiles based on levels of environmental familiarity and incorporated basic group behaviour, these additions often led to increased evacuation times due to delays associated with individual hesitation and limited coordination. In contrast, Chapter 5 enhanced the simulation model by integrating a willingness parameter and a message-spreading mechanism, allowing agents to influence others and initiate coordinated evacuation behaviour. When appropriately balanced, specifically with a suitable ratio of leaders to followers, these enhancements contributed to reduced evacuation times and improved flow dynamics. However, it is important to note that these benefits were not universal; in scenarios with low willingness or ineffective communication, the overall evacuation time increased. Therefore, while Chapter 5 offers a more behaviourally sophisticated and potentially more effective approach, its success is contingent upon the careful calibration of key parameters in relation to environmental complexity and crowd composition.

5.7 Threat Validation

Despite the advancements introduced in this chapter, several threats to validity and limitations must be acknowledged. The model's behaviour relies heavily on predefined assumptions about agent willingness and communication, which may not fully capture the complexity of real human responses during emergencies. For instance, the simulation assumes that once an agent receives a message, they respond immediately and correctly, overlooking possible misinterpretation, hesitation, or emotional resistance. Additionally, the results are sensitive to input parameters such as the number of leaders, willingness levels, and exit configurations. Minor adjustments to these variables may yield significantly

different outcomes, thus impacting the reliability and reproducibility of the results. The environmental setup is limited to a single room with two exits and fixed agent population sizes which further constrains the generalisability of the findings. Moreover, the communication model employed does not account for message delay, loss, or noise, which could influence group behaviour in more realistic contexts.

The simulation also lacks several key physical and psychological factors observed in real evacuations. There is no modelling of physical interactions, such as collisions or congestion effects near exits, nor is there any consideration of stress escalation or panic dynamics, which play critical roles in high-density scenarios. Agent roles are static, with no possibility for dynamic leadership changes, and all agents are treated as physically identical in terms of size and mobility. Lastly, the simplified architectural design, which excludes obstacles, partitions, or visibility obstructions, limits the extent to which the findings can be applied to complex, real-world environments. These constraints highlight the need for future research to incorporate richer agent diversity, dynamic role adaptation, and more realistic spatial and psychological modelling to enhance the validity and applicability of evacuation simulations.

5.8 Chapter Summary

Emergent behaviours like arching, herding, and leader-follower behaviour arise during panic situations due to complex interactions between individuals, their surroundings, and specific conditions. The willingness parameter, used in crowd simulation studies, is a type of victim agent's behaviour that emerges during the evacuation process. The efficacy and results of the evacuation process are strongly

impacted by the level of cooperation, adherence to instructions, and implementation of suitable actions exhibited by these agent agents.

Group evacuation is another important aspect of evacuation, influenced by group dynamics, leadership, communication, and peer influence. The performance of a group evacuation is influenced by factors such as the size of the group, interaction between members, the number of leaders, and the position of the leaders. This study examines the impact of many leaders present in a room during an evacuation, with the leaders situated in a coordinate system. The results show that increasing the number of agents in a simulation room decreases the effectiveness of employing the willingness parameter.

CHAPTER 6

CONCLUSION AND FUTURE WORK

6.1 Introduction

This chapter provides a concise overview of the primary contributions, limitations, discussions, and suggestions for further research. The conclusions of the thesis are presented in Section 6.2. In Section 6.3, the contributions in this thesis are presented. Section 6.4 presents the limitations and challenges, while Section 6.5 describes the future works. Section 6.6 explains our recommendations for future research. Finally, Section 6.6 presents the chapter summary.

6.2 Conclusions

Evacuation refers to the systematic procedure of evacuating individuals from a room or building in response to emergency circumstances, such as fires or earthquakes. The effectiveness of the evacuation process is dependent upon numerous circumstances. One aspect pertains to the individual's understanding of layout. In the absence of familiarity with the building layout, individuals rely exclusively on the evacuation plan.

In this research, the term "actual circumstances" refers to the critical real-world conditions experienced during emergency evacuations, such as fires, earthquakes, or other urgent threats that require people to exit a space safely and efficiently. These circumstances involve uncertain and dynamic environments, time pressure, restricted visibility (e.g., smoke), varying emotional responses (e.g., panic or hesitation), and the presence of both physical (walls, furniture) and social (crowd behaviour, communication) obstacles.

However, it is acknowledged that the simulation environment used in this study; a square, empty room without internal elements like furniture or partitions does not fully replicate the complexity of actual architectural layouts. The simplified room structure was chosen to control experimental variables, isolate specific behavioural factors (like willingness and message-spreading), and allow for focused testing of model parameters (e.g., social force values, leader-follower dynamics) in a manageable computational setting.

While this abstract room does not represent a real-world space such as an office, school, shopping mall, or hospital, it serves as a foundational testbed for studying the fundamental dynamics of agent-based evacuation behaviour. In future research, the scope will expand to include more realistic room configurations, such as multi-room layouts, hallways, furniture obstacles, multiple floors, and designated hazard zones. This would allow the model to be tested under conditions that more closely mirror the physical and social complexity of real evacuation scenarios, thereby increasing its applicability for use in architectural design, safety planning, and emergency preparedness simulations.

A simulation tool is employed to replicate the actual circumstances encountered during an evacuation. The implementation of a simulation tool has the potential to enhance the efficiency of evacuation procedures by introducing a novel approach to evacuating rooms or buildings. It is also possible to anticipate forthcoming circumstances in the event of unforeseen circumstances, such as the obstruction of any accessible route leading to the evacuation door.

The primary aims of this study are to create and implement an agent crowd steering simulation model for the purpose of mobile crowd steering. Additionally, the effectiveness of the proposed framework has been evaluated by comparing it to the original Social Force Model.

In Chapter 3, we have designed and developed an agent crowd steering simulation model for mobile crowd steering. A design for mobile crowd simulation that is built on agents is presented in this chapter. It includes the design of the model, the design of the modules, and the design of the algorithm. The agent crowd steering simulation model is now being explored further using the NetLogo simulation platform. In this instance, the initial SFM is constructed for the purpose of making a fire evacuation case study, which will serve as the benchmarking experiment for the remainder of the module development that will take place in the subsequent chapters.

In Chapter 4, we present the agent messaging model. We design the agent's communication. The simulation results are then compared to the results we collected in Chapter 3. This chapter presents a simulation for building evacuation that combines the SFM with a communication model. The communication model exemplifies the word-of-mouth (WOM) approach to disseminating information during the evacuation procedure.

Upon the initiation of word-of-mouth (WOM), the victim agent will assemble a group to follow the leader as they leave the room. The result shows that when DV is set to 1.5ms^{-1} , there is a slight increase in the evacuation time when the R2 setting is applied. The increased radius of message spreading suggests that the number of victim agents who establish a collective and adhere to the leader is higher in comparison to R1 configurations. The same result pattern is observed when the DV is equal to 1.5ms^{-1} . In

contrast to the experiments conducted in Chapter 3, the overall evacuation time for the experiment conducted in this chapter is comparatively shorter. The comparison of evacuation ticks is made between the experiment conducted in Chapter 3, which was conducted without a group, and the experiment conducted with a group (Chapter 4), both of which were conducted using a single exit door. By combining grouping techniques with message forwarding, the number of evacuation ticks increases by a range of 4% to 31%. When the value of N is 100, the proportion is relatively high: 28% for DV = 1.0 and 31% for DV = 1.5. Nevertheless, as N increases from 200 to 500, the rate of increase, decreases. In general, across all simulation scenarios, there was a significant increase in mean velocity observed during the initial evacuation phase, followed by a gradual decrease.

In Chapter 5, we present the willingness of agent and leader-follower behaviour. The inclusion of the willingness parameter has the potential to decrease the overall evacuation time, provided that the number of leaders aligns with the unique dimensions and layout of the room. Nevertheless, the decrease in time is minimal. The findings of the simulation align with the research conducted by Ma et al. (2022), indicating that an increase in the number of individuals wanting to evacuate leads to a prolonged duration of the overall evacuation period. According to Gray-Graves et al. (2011), when a group is completely cooperative, the efficiency of evacuation increases during emergencies and the level of uncertainty lowers during evacuation. We incorporated the attribute of willingness into the SFM and enhanced the ability of victim agents to spread messaging, subsequently examining the results. The time to evacuate the building increases by 2.20 % for 100 individuals, and the simulation duration increases by 23.29 % with three leaders and 200 people. When using willingness parameters, two leaders increase value

by 26.25 %. When the values of willingness and DV are both adjusted to 0, the total evacuation in ticks is observed to decrease by 28.59%. With a sample size of $N = 100$ and a willingness level of 1, the evacuation time is decreased by 44.71% compared to the experiment conducted in Chapter 3.

However, when the values of willingness and DV are both adjusted to 0, the total evacuation in ticks is observed to decrease by 12.28%. With a sample size of $N = 200$ and a willingness level of 1, the evacuation time is decreased by 15.80% compared to the experiment conducted in Chapter 3. As seen, there is an average increase of 104.6% in the overall evacuation time when the value of N is increased from 100 to 200. The rise in evacuation time observed at $N = 200$ can be ascribed to the delay in evacuation caused by the victim agent's efforts to allocate time towards disseminating the message to nearby victim agents.

The overall study's results indicate that the effectiveness of evacuation is diminished in situations where populations with limited cooperation possess sufficient evacuation information. The reason for this is because there were less victim agents who joined the group as they moved towards the exit door. This phenomenon is the source of this situation.

6.3 Contributions

The work described in this thesis concerns the modelling of evacuation simulation models for room layout settings. Specifically, the major contributions of this thesis are listed as follows:

- i. Agent simulation model for mobile crowd evacuation system.

In this study, an agent simulation model for the simulation of mobile crowd steering in the context of evacuation scenarios is proposed. The development of our models is derived from the pre-existing mobile guidance system mentioned in the review. The models comprise four modules that have the potential for future expansion.

- ii. Agent messaging model.

In the fourth chapter, the messaging model is introduced as a means to integrate the capacity of victim agents to spread messages to other victim agents during the evacuation process. The process of message spreading occurs when a victim agent comes into contact with another victim agent who is located within a specific radius.

- iii. Leader-follower model for crowd steering.

A leader-follower model is presented for simulating crowd direction during the evacuation process. According to the leader-follower model, a victim agent possesses the potential to assume a leadership role and provide guidance to fellow victims, provided they possess a sufficient level of knowledge value.

6.4 Limitations and Challenges

The agent crowd steering simulation model has several limitations. Due to the message that they have received, they are unable to change their roles and, consequently, recalculate the path. Furthermore, in order to facilitate the separation of leaders, the roles of leaders are fixed to a certain extent. One additional issue to consider is the absence of

furniture within the area, such as chairs, tables, or even a flower vase, which has the ability to influence the results of the simulation.

From the review, several challenges in agent-based crowd steering involve:

i. Simulation of automatic steering is complex.

According to Sud et al. (2007b), the task of simulating autonomous steering has significant challenges. This phenomenon can be attributed to the natural capacity of each agent to autonomously navigate towards their respective target (Zhao & Winter, 2016). Every individual agent has the autonomy to pursue their own aim or make their own choices, and the methods employed to achieve these objectives may differ from those followed by other agents. The study conducted by Shendarkar et al. (2008) focuses on the autonomous control of steering in busy settings and the scalability of steering algorithms.

ii. Complexity in steering algorithm.

The current steering methodologies exhibit variations based on their primary objectives. The common approaches are based on finding the nearest exit based on the shortest path, using Dijkstra's algorithm as in Rahman et al. (2008), Wu et al. (2013), Patil et al. (2011), Chen and Feng (2009), Tsai et al. (2018), Shendarkar et al. (2008), Qiu and Hu (2010), Guy et al. (2010) or using A* pathfinding algorithm as in Foudil et al. (2009), Kala et al. (2018), Juniastuti et al. (2016), Oliva and Vilhjálmsón (2014), Rojas et al. (2013), Van Toll et al. (2012) and Sud et al. (2007b). The simulation model's environment may include static obstacles, such as walls and furniture, as well as dynamic obstacles, such as other agents.

Therefore, steering should incorporate collision avoidance to ensure the safe navigation of agents from their initial location to the desired goal position. However, the task of guiding agents in densely populated locations poses significant challenges due to the extremely dynamic nature of the environment. In this scenario, it is necessary to provide the agent with real-time information regarding the position, velocity, and heading of other agents in order to mitigate possible congestion that may arise in bottleneck locations. Conventional steering methods used in evacuation scenarios are not suitable for extremely dynamic situations where the routes assigned to individuals may vary over time. Individuals should be provided with flexible routes that may adjust to their surroundings in order to guarantee the highest level of safety for everyone.

While the proposed agent-based crowd steering simulation model successfully integrates behavioural elements such as willingness and message communication, it still presents several notable limitations that constrain its applicability in real-world evacuation scenarios.

A key limitation is the inflexibility of agent roles. Once an agent receives a message and assumes the role of a follower or leader, it is unable to dynamically change that role or recalculate its evacuation path in response to new environmental cues. This static role assignment restricts agents' ability to adapt to evolving evacuation conditions, such as encountering congestion, changing crowd flow directions, or discovering alternative exits. The model also imposes fixed leader roles, primarily to facilitate group

formation and steering behaviour. However, in reality, leadership can shift fluidly during emergencies, with individuals stepping up or deferring based on the situation. This constraint may reduce the simulation's realism and limit its ability to capture emergent, spontaneous group behaviour.

Another limitation lies in the absence of environmental complexity. The simulation environment is simplified, lacking physical elements such as furniture, fixtures, or movable objects (e.g., chairs, tables, flower vases), all of which could significantly influence agent movement and path selection. These objects may obstruct visibility, create choke points, or modify agent behaviour through avoidance strategies. The omission of such factors reduces the ecological validity of the model and may lead to an underestimation of congestion or delay during evacuation.

From a technical standpoint, the simulation also faces challenges related to the complexity of automatic steering algorithms. Simulating autonomous agent movement requires addressing the individuality of each agent's decision-making process and pathfinding behaviour. Each agent, acting as an independent entity, may choose different strategies to reach their goal. As pointed out by Sud et al. (2007b) and Zhao & Winter (2016), replicating this decentralised autonomy in a simulated environment is inherently complex and computationally demanding, especially in large-scale crowd scenarios.

Additionally, the steering algorithms implemented in the model do not fully capture the sophistication required for navigation in densely populated, dynamic environments. Most conventional evacuation simulations rely on algorithms such as Dijkstra's or A*, which prioritize the shortest path. While these methods are efficient for basic pathfinding, they fall short in scenarios where the environment is continually

changing due to moving agents or the emergence of unexpected bottlenecks. In such cases, agents require real-time data on their surroundings; such as the position, velocity, and trajectory of nearby individuals; to avoid collisions and re-route effectively. The absence of adaptive, real-time steering mechanisms in the current model limits its ability to respond to high-density, rapidly evolving conditions that are typical of emergency evacuations.

In conclusion, while the proposed model provides a foundation for simulating communication and behavioural influence during evacuation, its inability to handle dynamic role reassignment, environmental complexity, and real-time adaptive steering represents significant limitations. Addressing these issues in future work will be essential to improve the model's realism, flexibility, and applicability to real-world evacuation planning and safety assessments.

6.5 Future Works

This study primarily focused on the development and simulation of evacuation dynamics using computational models, particularly emphasising communication behaviours and willingness parameters. However, the empirical validation of these behavioural assumptions, specifically through real-world testing involving human participants was beyond the scope of this research. Future work should involve experimental studies or controlled evacuation drills to observe how individuals respond to communication messages and how willingness to evacuate evolves in actual emergency scenarios. Such empirical analysis would provide valuable data to calibrate the simulation model more accurately, validate behavioural parameters, and identify discrepancies between simulated and real

human behaviour. In particular, measuring how messages are interpreted, how quickly individuals act upon them, and how leadership and group dynamics form in real time can significantly enhance the realism and reliability of the model. Incorporating these findings will contribute to building more robust evacuation planning tools that align closely with human psychological and social responses during emergencies.

Future works could improve the evacuation simulation model by adding a dynamic representation of user awareness of the evacuation procedure. The paradigm currently assumes that agents become aware of the situation solely via direct message transmission or environmental indicators. In real-life scenarios, individuals may have differing levels of pre-existing awareness influenced by prior experiences, familiarity with the place, availability of signage, or exposure to public statements. To reflect this, agent profiles may be augmented to incorporate a “awareness index” that affects their decision-making velocity, route selection, and willingness to collaborate. For instance, agents possessing heightened awareness may commence evacuation more swiftly or assume informal leadership roles, whereas those with lower awareness may depend more on social signals or experience disorientation. The model might also resemble proactive information dissemination, using visual alerts or auditory signals, to investigate the impact of early warnings on evacuation timing and coordination. Incorporating awareness as a variable will enable the simulation to more precisely replicate real-world human behavior and yield significant insights for formulating efficient evacuation strategies for communication.

6.6 Recommendations for Future Research

Considering the model and the research results, we would like to suggest a few new elements that would greatly improve the evacuation simulation model.

- i. Social interaction among victim agents.

Additional research is required to investigate the application of social interaction in crowd control during emergency evacuation for various reasons. One of the various justifications for implementing social interaction among agents is the occurrence of situations such as the disruption of communication networks. The transmission of information regarding hazards and evacuation routes between individuals, either directly or through a simulated agent-to-agent model, has the potential to be lifesaving.

- ii. Flexible layout design.

In order to enhance the assessment of the efficacy of the suggested agent crowd steering simulation model, it is imperative that the layout design exhibits flexibility and is capable of accommodating the maximum number of victimagents, dependent upon the dimensions of the layout. In addition to the dimensions of the layout, it is important to take into account the potential for including additional exit doors. Research has demonstrated that the inclusionof many exit rooms leads to a significant decrease in evacuation duration in comparison to a room with a single exit. In the event of a multi-floor building,the evacuation efforts would be intensified because victims would need to spend more time escaping the

building because they would have to go down several stairs before reaching the exit door.

- iii. The observable representation of hazards.

The enhancement of the simulation model's performance can be achieved by increasing the visibility of smoke or fire. When smoke or fire is observed, persons may change their speed and direction as they try to avoid the area affected by smoke and fire.

6.7 Chapter Summary

This chapter concludes the study by summarizing the design, development, and evaluation of an agent-based evacuation simulation model that integrates behavioural parameters such as communication and willingness to evacuate. The study was conducted in three progressive stages. In Chapter 3, a baseline simulation using the original Social Force Model (SFM) was developed to simulate agent movement during a fire evacuation scenario, serving as a benchmark for subsequent enhancements. Chapter 4 introduced a communication mechanism using a word-of-mouth (WOM) approach, allowing agents to transmit evacuation messages to others within a specified radius. This led to the emergence of leader-follower groups that improved early coordination, although a slight increase in evacuation time was observed due to the time spent forming groups and spreading messages. Chapter 5 further incorporated a willingness parameter, enabling agents to exhibit different levels of motivation to evacuate. Results demonstrated that, under optimal conditions, such as an appropriate number of leaders and room design, the evacuation time significantly decreased; by as much as 44.71% in some scenarios. However, in denser simulations,

message spreading caused delays, and overall efficiency gains were modest. This chapter also discusses the effectiveness of evacuation in various situations, focusing on the use of an agent crowd steering simulation model for mobile crowd steering. The study uses the NetLogo simulation platform to create an agent crowd steering simulation model for mobile crowd simulation, comparing it to the original Social Force Model. The agent messaging model exemplifies the word-of-mouth approach to disseminating information during the evacuation process. The study found that the effectiveness of evacuation decreases in situations where populations with limited cooperation have sufficient evacuation information, as there are fewer victim agents joining the group. Future research should focus on improving evacuation efficiency and incorporating more cooperative behaviours into the system. The study also highlights the need for further research on social interaction among victim agents, flexible layout design, and increasing visibility of smoke or fire to enhance the simulation model's performance. The overall findings contribute an agent-based model that simulates both physical movement and social behaviours during evacuation, offering practical insights for emergency planning. Nonetheless, limitations remain, including fixed agent roles, absence of environmental complexity such as furniture, and a lack of real-time adaptive pathfinding. Future work should include empirical validation through evacuation drills, integration of user awareness levels, hazard visualization, and more realistic architectural layouts. These enhancements are essential for improving the model's accuracy, adaptability, and applicability in real-world evacuation planning and safety design.

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APPENDICES

Appendix A: Journal Publications

1. **Hussain, N.** & Shiang, C. W. (2022). Modelling of crowd evacuation with communication strategy using social force model. *Journal of Optimization in Industrial Engineering*, 15(1), 233-241.
2. **Hussain, N.**, Shiang, C. W., Loke, S., & bin Khairuddin, M. A. (2022). A Multi-Agent Simulation Evacuation Model Using The Social Force Model: A Large Room Simulation Study. *JOIV: International Journal on Informatics Visualization*, 6(1-2),221-229.