Designing an Agent Based Simulation Framework for AI-Driven Flood Evacuation Analysis

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Abstract

The need for efficient flood evacuation strategies is escalating due to the escalating climatic variability and expanding urbanisation. This dissertation addresses the issue of improving flood evacuation tactics in limited spaces, namely subterranean tube networks. The paper presents a novel simulation framework that integrates Artificial Intelligence (AI) for decision-making and optimisation through the use of Agent-Based Simulation (ABS). The simulation framework's design is built upon the principles of Engineering Agent-Based Social Simulation (EABSS), which offers a solid foundation and conceptual framework for simulating realistic and dynamic social interactions.

The integration of the Social Force Model (SFM) is employed in the AI component to simulate human behaviour and population dynamics in the context of flood occurrences. The GAMA modelling platform is employed to create a fundamental flood simulation within an underground tube network, which serves as a testing ground for the implementation of AI logic based on SFM. The solution allows the agents within the simulation to not only adhere to established evacuation protocols but also adjust and make judgements in response to real-time circumstances. Through the incorporation of various methodologies, the framework offers intricate observations on the effectiveness of existing evacuation procedures and highlights potential avenues for improvement, thus facilitating the development of more sophisticated and adaptable approaches.

The results of this investigation make a valuable contribution to the growing body of scholarly literature in the fields of emergency evacuation planning and AI-driven social simulations. Moreover, it provides a scalable and flexible instrument for decision-makers, planners, and emergency services to evaluate and execute more efficient evacuation methods in practical subterranean transportation systems, therefore mitigating hazards and potentially preserving lives.

Keywords: Agent-Based Simulation (ABS); Engineering Agent-Based Social Simulation (EABSS); Social Force Model (SFM); GAMA modeling platform; flood evacuation; Artificial Intelligence (AI); underground tube networks; emergency planning; adaptive strategies; human behavior simulation.

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Chapter 1

Introduction

1.1 Motivation

Due to extraordinary climate instability and urbanisation, flood evacuation procedures must be implemented immediately. Constrained and highly occupied places such beneath underground networks make evacuation harder. Traditional evacuation models are beneficial, but they cannot give dynamic and flexible solutions for extremely unexpected events. To ease evacuations, a framework must be flexible, adaptable, and sensitive to real-time data. This paper develops an AI-integrated Agent-Based Simulation (ABS) framework to solve this research need. The system relies on Engineering Agent-Based Social Simulation (EABSS). Real social interactions are important to the EABSS framework's comprehensive conceptual paradigm.

1.2 Aims and Objectives

The major aim of this project is to construct a sophisticated simulation framework based on the Agent-Based Simulation (ABS) approach, with a specific focus on subterranean tube networks. The objectives intended to accomplish this objective are as follows:

- This study endeavours to develop a comprehensive Agent-Based Social Simulation (ABSS) framework that effectively emulates flood evacuation scenarios within confined spaces, in alignment with the principles of Engineering Agent-Based Social

Simulation (EABSS) outlined in the extended abstract.

- This study suggests the incorporation of artificial intelligence (AI) approaches, specifically the Social Force Model (SFM), to improve existing evacuation strategies and offer prompt decision support for emergency personnel.

  key aim of this study is to provide a framework that can help assess the potential threats linked to evacuations and provide efficient techniques to limit these risks, thereby enhancing the safety of both evacuees and emergency personnel.

Utilising a simple but rigorous simulation with the GAMA modelling platform and SFM, this study has successfully achieved all of its objectives. As a result, a fundamental model has been established that can serve as a foundation for future research and development efforts. The incorporation of the Social Force Model into the artificial intelligence component adds a level of social realism to the simulation, thereby enhancing its applicability and relevance to real-world scenarios. This synthesis offers a novel approach for investigating patterns and potential applications in future research and practical endeavours.

1.3 Description of the work

The dissertation is divided into seven chapters that outline the problem and discuss possible future projects based on the findings. Chapter 2 reviews the contextual basis and relevant scholarly works to assess the current state of Agent-Based Simulation (ABS), Artificial Intelligence (AI) approaches for evacuation objectives, and underground tube network challenges. EABSS and SFM are used as core theories in the study, boosting system robustness and dependability. Chapter 3 of this study discusses the design features, explaining the ABS framework's structure and components. Chapter 4 covers pragmatic implementation, including using the GAMA modelling platform for simulation and integrating AI methods. Chapter 5 evaluates the framework and assesses its ability to achieve the goals. This review sheds light on the framework's efficacy and suggests improvements. In conclusion, Chapters 6 and 7 evaluate the project and suggest future research.

Chapter 2

Background and Related Work

2.1 Introduction to Literature Review

The increasing development and reliance on underground transport networks in metropolitan areas necessitates a comprehensive understanding of human behaviour in emergency scenarios. Simulation tools have played a prominent role in these investigations, facilitating the analysis and prediction of diverse facets of the evacuation process. These tools offer valuable insights on the timeframes of evacuations, identifying bottlenecks, assessing the effectiveness of evacuation plans, and understanding the multitude of variables that impact the evacuation process.

This Literature Review intends to achieve the following:

- Provide a systematic overview of existing models, methodologies, and simulations related to emergency evacuations, emphasizing metro station contexts.
- Illuminate the complexities of human behaviors during emergencies, examining the role and implications of agent-based models and other simulation techniques.
- Highlight the challenges and constraints faced in evacuation simulations, considering the multifaceted nature of environmental conditions, architectural designs, and human behaviors.

This review examines a vast array of scholarly works, case studies, and applications of simulation models in the domain of emergency evacuations. However, this analysis has inherent limitations. While it strives for completeness, the expansive and ever-changing nature of the discipline means that not every nuance or recent development may be discussed. In addition, the emphasis on metro station evacuations could lead to a reduction in coverage of other equally crucial emergency evacuation contexts. Nonetheless, the primary objective remains: to provide a comprehensive picture of the current state of knowledge and a foundation for future research.

2.2 Historical Context and Importance of Flood Evacuation

Floods possess immense destructive potential, impacting millions of individuals worldwide, resulting in substantial economic ramifications and, regrettably, loss of human lives. In metropolitan locations, particularly in places with subterranean infrastructure like metro stations, the consequences can be exceptionally severe [21]. Carrington (2016) underscored the significance of the issue by pointing out that a total of 57 metro stations in the city of London are situated in areas that are highly susceptible to flooding. This observation serves to emphasise the criticality of this worry for urban planners and relevant authorities [21].

The implementation of efficient flood evacuation strategies is of utmost importance in such circumstances. The primary goal of these strategies is to facilitate the expeditious and secure evacuation of individuals from high-risk areas to more secure destinations. The study conducted by Yu et al. (2018) centred on the process of evacuating passengers from fire disasters occurring in railway tunnels. The research emphasised the complexities associated with evacuating large numbers of individuals in confined underground environments [11]. Comparable issues are expressed in research focused on the evacuation of metro stations during different emergency situations [5,7]. The focus of these studies highlights the importance of prompt and organised evacuations in reducing possible casualties.

Nevertheless, the process of attaining a smooth evacuation procedure in the event of floods is fraught with several obstacles. The dynamics of evacuation are intricate and are influenced by a multitude of elements, encompassing the built environment as well as human psychology. Computer simulations have emerged as an indispensable tool within this particular domain. The utilisation of agent-based modelling enables researchers to imitate and comprehend human behaviours within evacuation scenarios, hence helping the development of efficient evacuation strategies [2,3]. Chen emphasised the significance of conducting agent-based research to examine crowd interaction in emergency evacuations [2]. In a similar vein, Zheng et al. utilised a cellular automaton methodology to replicate the intricate processes of pedestrian evacuation in the presence of subterranean inundation, thereby providing valuable insights into the pivotal obstacles and regions warranting attention [12].

Notwithstanding these achievements, there are still some difficulties that persist. The presence of diverse crowds, the variety in individual reactions, and the inherent unpredictability of flooding are some of the variables that contribute to the complexity of evacuation dynamics. In their study, Sun and Wu introduced a heterogeneous cellular automata model as a means to capture the various population behaviours that occur during emergency evacuations [8]. These models demonstrate the complex and diverse range of issues associated with flood evacuations, highlighting the importance of implementing adaptable, dynamic, and thorough evacuation strategies.

2.3 Agent-Based Simulation (ABS) in Emergency Evacuation

Agent-Based Simulation (ABS) is a sophisticated computational method that models the behaviour of individual agents and their interactions with their environment [14]. ABS has proven to be an effective tool for simulating complex emergent phenomena in numerous domains, such as emergency evacuations.

2.3.1 Principles of ABS

ABS is based on the notion that global system behaviour emerges from the interactions of individual agents with unique characteristics and decision-making processes [5]. Typically, each agent is viewed as an independent entity with distinct properties and the capacity to adapt based on internal rules or interactions with its environment. By simulating the actions and interactions of these individual agents, ABS aims to recreate and predict the collective behaviour of systems [14].

2.3.2 Use cases of ABS in emergency scenarios

Frequently, emergency evacuation scenarios involve complex behaviours that depend on a variety of variables, such as the nature of the emergency, the density of the crowd, and the physical infrastructure of the evacuation environment. Chen [2] notes that ABS has been used extensively to examine crowd interactions during emergency evacuations. Edrisi et al. Li et al. [6] proposed a numerical simulation strategy to predict the evacuation behaviour of building occupants during earthquakes in a separate study. In addition, Zheng et al. [12] utilised cellular automaton, a type of ABS, to simulate the evacuation dynamics of pedestrians in situations involving the spread of underground floods. In addition, ABS has been used to comprehend and improve evacuation procedures in specific environments, such as underground metro stations, particularly in the face of challenges such as fires [11]. ABS models' adaptability enables scenario-based evaluations, which can assist decision-makers in optimising evacuation strategies and infrastructure design.

2.3.3 Benefits and limitations of using ABS for emergency evacuation

Benefits:

- *Granularity and Detail:* ABS provides a detailed representation of individual agent behaviours, thereby facilitating a greater comprehension of emergent phenomena [14].

- *Flexibility:* ABS models are easily adaptable to different scenarios, making them versatile tools for the study of a variety of emergency situations [16].
- *Scenario Analysis:* ABS is capable of simulating various scenarios, which aids in the planning and optimisation of evacuation strategies [2].

Limitations:

- *Complexity:* ABS model design and calibration can be difficult, particularly for large-scale scenarios [4].
- *Validation:*For ABS models to accurately represent real-world behaviours, rigorous validation processes are required [1].
- *Computational Demands:* Superior fidelity ABS models may necessitate substantial computational resources, limiting their scalability [9].

2.4 Engineering Agent-Based Social Simulation (EABSS)

2.4.1 Definition and principles

Engineering Agent-Based Social Simulation (EABSS) is a framework in which agent-based modelling techniques are designed and structured specifically for simulating social processes and phenomena (Figure 2.1 (source:[13])). This paradigm integrates computational engineering and social systems, providing a granular view of individual-based decision-making processes and their collective impact on larger system dynamics. [14] Siebers and Davidsson provide a comprehensive introduction to the field, emphasising its utility in simulating and comprehending complex social systems via computational means.

EABSS is based on the design and validation of agent-based models that replicate social situations in the real world. This requires a systematic approach, typically including problem analysis, information gathering, and case studies. Siebers et al. [16, 17] outlined a detailed framework that includes key activities such as defining scope, archetype stencils, agent/object stencils, interactions, and ultimately setting up the artificial lab to

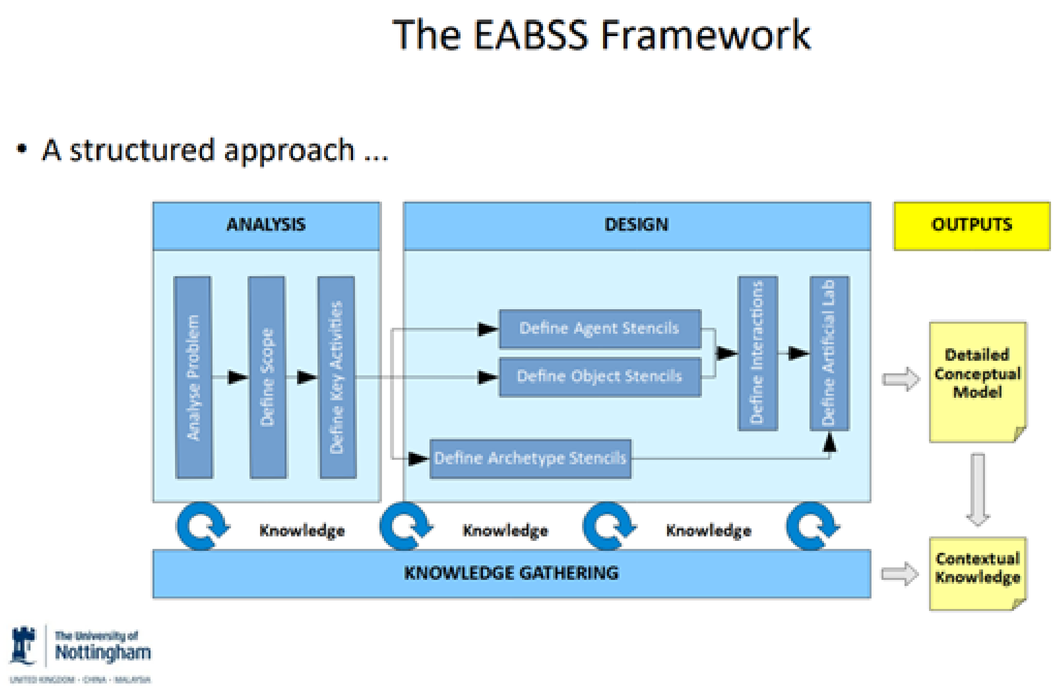

Figure 2.1: EABSS Framework

test the model. The ultimate goal is to generate accurate and insightful simulations for policymaking, social analysis, and further research.

2.4.2 Importance in ABS for social and engineering systems

The intersection of Agent-Based Simulation (ABS) and social systems represents a significant advance in computational social science. ABS has traditionally been utilised in a variety of fields, ranging from ecology to economics, but its application to social systems presents a multitude of new challenges and opportunities. EABSS's ability to capture emergent behaviours, take individual heterogeneity into account, and provide a microscopic view of interactions renders it indispensable for comprehending complex social phenomena.

EABSS provides a robust analysis platform for human-centric and coupled human-natural systems [16]. By modelling agents that mimic human decision-making patterns and observing their behaviour in a simulated environment, researchers can gain profound insights into socioeconomic and environmental interactions. This is essential not only for academic knowledge but also for practical solutions to pressing global issues.

2.4.3 Application examples and limitations

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2.5 Social Force Model (SFM) in Crowd Simulation

2.5.1 Introduction to the Social Force Model

The Social Force Model (SFM) is a fundamental concept in crowd simulation intended to simulate the behaviour of individuals within a crowd. At its core, SFM is based on the premise that social forces exert influence over the movements of individuals within a crowd. The components of these forces include repulsion from obstacles, attraction to destinations, and interactions with other individuals. These components are utilised by the SFM to simulate the collective behaviour of a crowd [5][6].

2.5.2 How SFM Emulates Human Behavior in Crowds

By simulating a complex interplay of forces, SFM mimics human behaviour within crowds. SFM considers two fundamental types of forces:

1. Desired Movement Force: This force represents a person's intention to move towards

a specific destination. Typically, it is directed towards a specific location and drives the agent there [1].

2. Social Forces: Social forces emerge from interactions with other agents and environmental obstacles. These forces can be categorised into various sub-forces:

    - Repulsion from Agents: Agents tend to maintain a certain personal space around themselves, resulting in a repulsive force when others encroach upon this space [4].
    - Attraction to the Destination: To reach their intended destination, individuals are attracted to it and experience an attractive force in that direction [5].
    - Repulsion from Obstacles: Obstacles, such as walls or barriers, generate repulsive forces to prevent agents from colliding with them [12].
    - Interaction with Neighbours: Agents influence each other's movements by interacting with their neighbours. These interactions can involve forces of alignment, cohesion, and separation [6].

    This combination of forces directs the agent's movement, resulting in realistic crowd behaviour that takes into account personal space, collision avoidance, and interactions with nearby individuals.

2.5.3 SFM in the Context of Emergency Evacuation

Several studies have successfully simulated emergency evacuations using SFM, revealing the complexities of crowd behaviour in hazardous situations. Chen et al. (2017) used agent-based research to study emergency evacuation crowd interaction [2]. Their research illuminated how people react to emergencies, adapt to change, and influence each other in a crowd. SFM can be used to understand and simulate emergency evacuations in complex environments like underground metro systems, as shown in this study.

According to Li et al. (2018), numerical simulation can predict occupant evacuation behaviour during building evacuations [6]. SFM was used to model earthquake-induced evacuations. The study showed that SFM can capture a wide range of emergency behaviours, providing valuable information for safety protocols.

Siebers et al. (2018) proposed a design pattern [25] for applying social forces to human-centric simulation models. Although not focused on evacuation, their work expands our understanding of how SFM can be integrated into human behaviour simulations.

SFM is effective at simulating emergency evacuation crowd behaviour. Its ability to mimic human behaviour, consider social interactions, and adapt to different environments makes it useful in agent-based simulations to improve evacuation strategies and safety. Chen, Li, and Siebers et al. show that SFM can be used to solve emergency evacuation problems, especially in confined spaces like underground tube networks.

2.6 GAMA Modeling Platform

For agent-based modelling and simulation, the GAMA modelling platform is a flexible and effective tool [23]. Scholars can create, test, and analyse agent-based models in a comprehensive environment with it, which makes it a valuable tool for researching complex systems like flood evacuation scenarios. We will examine GAMA's overview, its use in agent-based modelling and simulation, and its applicability to flood evacuation scenarios in particular in this section.

2.6.1 Overview of GAMA

"Generalised Architecture for Modelling and Simulations," or GAMA, is an open-source modelling and simulation platform with a feature-rich feature set and an easy-to-use interface for creating agent-based models [23]. Because of its highly configurable design, researchers can tailor agents, environments, and interactions to their own research questions and goals. Because GAMA has a visual modelling interface, users with different levels of programming experience can use it. Furthermore, GAMA facilitates the integration of different modelling paradigms, such as agent-based modelling, differential equations, and cellular automata [23, 26].

2.6.2 Utility in Agent-Based Modeling and Simulation

GAMA is an invaluable tool for a variety of applications, including the modelling and simulation of complex systems across multiple domains, thanks to its flexibility and extensibility. GAMA can be used by researchers to investigate emergent behaviours, examine system dynamics, and evaluate the effects of various parameters and variables on model results [23, 26]. Researchers can examine real-world scenarios in detail thanks to the platform's support for parallel computing and large-scale simulation capabilities.

2.7 Integration of ABS, AI, and SFM

In the context of flood evacuation analysis, the integration of Agent-Based Simulation (ABS), Artificial Intelligence (AI), and Social Force Model (SFM) plays a crucial role in enhancing the understanding and optimization of evacuation strategies.

Balci and Sargent (1984) emphasize the importance of validating simulation models, a process where AI techniques can be instrumental in improving model accuracy and performance [1]. Taylor et al. (2015) discuss the relevance of simulation in various domains, highlighting AI's role in advancing simulation methodologies [9]. These studies underline the synergy between ABS and AI, with AI techniques aiding in the creation and validation of ABS models.

Chen (2017) explores agent-based research on crowd interaction in emergency evacuation scenarios, demonstrating the integration of AI-driven agents into ABS simulations [2]. Similarly, Edrisi et al. (2021) present a study on simulating metro station evacuation, employing agent-based exit choice models that incorporate AI elements [3]. These studies showcase the integration of AI techniques into ABS for simulating crowd behavior during evacuations, which is vital for understanding and improving evacuation strategies.

While there are notable examples of ABS and AI integration in evacuation simulations, there remains a gap in the literature concerning the integration of SFM, which emulates individual behaviors within crowds, into ABS frameworks. SFM has shown promise in modeling human movement during emergencies (Gwynne et al., 1999) [4], and its integration with ABS could provide a more realistic representation of evacuee behavior.Additionally, the combination of ABS, AI, and SFM in the specific context of flood evacuation within underground tube networks is an underexplored area. Most of the existing studies focus on broader emergency evacuation scenarios. Future research should concentrate on tailoring these techniques to the unique challenges posed by underground environments, taking into account factors like confined spaces, limited exit options, and the impact of flooding.

2.8 Risk Assessment and Mitigation in Underground Tube Networks

2.8.1 Unique Challenges of Underground Tube Networks

In urban areas, the subterranean tube networks constitute essential transportation infrastructure. But when it comes to assessing and mitigating flood risk, they have unique difficulties. The intricate and linked structure of subterranean stations, constrained escape routes, and the possibility of sudden flooding in cramped areas are some of these difficulties [21]. Researchers have resorted to sophisticated simulation methods like Agent-Based Simulation (ABS) and the incorporation of Artificial Intelligence (AI) components in order to tackle these challenges. These tools make it possible to model intricate evacuation plans and evaluate the risks that could arise from flooding [3].

2.8.2 Approaches to Risk Assessment

In underground tube networks, risk assessment entails assessing possible risks along with their likelihoods and effects. This evaluation is essential for locating weak points and putting good mitigation plans in place.

ABS and AI techniques have been used in recent studies to simulate the evacuation of metro stations during flood events. For instance, Edrisi et al. (2021) simulated the evacuation process by taking into account different exit options and passenger behaviours using agent-based exit choice models [3]. Furthermore, Taylor et al. (2015) stressed the value of simulation in risk assessment since it enables the assessment of multiple scenarios and the detection of vulnerabilities [9].

2.8.3 Strategies for Risk Mitigation

An integrated strategy is needed to reduce the risk of flooding in subterranean tube networks. This entails strengthening emergency response protocols, fortifying infrastructure resilience, and utilising technology to provide early warning and monitoring.

Enhancing voice alarm systems in subterranean stations, which are essential for emergency communication during floods, was the main focus of Gomez-Agustina's (2013) research [18]. In a similar vein, Carrington (2016) emphasised that in order to reduce the effects of flooding, proactive flood risk assessment and early warning systems in underground stations are essential [21].

Additionally, optimising crowd movement during emergencies through the integration of AI and ABS into evacuation plans can lessen traffic and increase safety [5]. Furthermore, Zheng et al. (2019) have shown that cellular automata models can be used to simulate the dynamics of evacuation during underground flood scenarios [12].

To summarise, the processes of risk assessment and mitigation in subterranean tube networks are intricate yet crucial. Improved infrastructure design, AI integration, and recent developments in simulation methods are all helping to make flood risk management in these vital urban areas more successful.

2.9 Summary and Research Gaps

The reviewed literature on flood evacuation simulations using agent-based modeling (ABM) and related techniques provides valuable insights and contributes significantly to our understanding of emergency evacuation scenarios. This section summarizes key findings from the literature, identifies research gaps, and justifies the need for the present study.

2.9.1 Summary of Key Findings

The reviewed literature highlights emergency evacuation simulation trends and findings. Chen et al. (2017) and Edrisi et al. (2021) show that agent-based modelling (ABM) can accurately model crowd behaviour during evacuations [2][3]. As shown by Li et al. (2022) and Sun and Wu (2022), AI-driven decision support systems can improve evacuation strategies [5].[8]. EABSS is a crucial toolkit for modelling complex social systems, which fits flood evacuation challenges [14]. Siebers et al. (2018)'s design pattern for embedding SFM into simulation models [15] shows its importance in understanding evacuation crowd behaviour. GAMA's adaptability and suitability enable it to simulate complex scenarios like underground tube network evacuations [23].

2.9.2 Identification of Research Gaps

While the existing literature offers valuable insights, several research gaps are evident:

Limited Application to Underground Tube Networks

Many studies examine metro station or general emergency evacuation scenarios [2][3][8]. Underground tube networks' confined spaces and complex structures can complicate evacuation strategies, so more research is needed [20][21].

Limited AI Integration in Flood Evacuation Simulations

While some studies [5][8] introduce AI techniques, there is a lack of research that thoroughly examines how AI can be integrated for real-time decision support in flood evacuation scenarios, especially in underground environments.

Scarcity of Comprehensive Risk Assessment and Mitigation Strategies

The literature review discusses risk assessment and mitigation [5][21], but more investigation is required to create all-encompassing plans for guaranteeing the security of people and emergency responders during evacuations of the subterranean tube network.

2.9.3 Justification for the Present Study

Given the research gaps and the growing importance of optimising flood evacuation strategies, this study addresses them. This research develops an Agent-Based Simulation Framework for AI-Driven Flood Evacuation Analysis in underground tube networks to improve safety and decision-making during flood events in confined spaces. AI techniques, the Social Force Model, and the GAMA modelling platform offer a unique approach to these challenges and advance flood evacuation simulations.

The reviewed literature emphasises agent-based modelling, AI integration, and social force modelling in flood evacuation simulations, which underpins this study. Due to research gaps, this dissertation seeks to investigate underground tube network evacuations.

Chapter 3

Design

As part of the process of developing a solid and reliable modelling framework for flood evacuation analysis in subterranean tube networks, a conceptually sound and well-organized design must arise first. A fundamental strategy was used to accomplish this, utilising the ideas of Engineering Agent-Based Social Simulation (EABSS) framework(Figure 2.1). This conceptual model served as the foundation for creating the entire simulation process, specifying the prerequisites, and outlining the plan for the next stage of implementation inside the GAMA modelling platform. Even though developing a thorough and highly flexible GAMA model is the ultimate objective, it's crucial to remember that some simplifications were purposefully added. The aforementioned simplifications are intended to achieve a compromise between practicality and complexity, guaranteeing that the final GAMA model is both concise and versatile enough to be applied to the modelling of flood evacuation scenarios in subterranean tube networks. The design phase serves as a vital link between the broad goals of the research and the actualization of a simulation model that can successfully handle the intricate problems related to flood evacuation analysis. The knowledge gathering section are a collection of information deduced from literature sources which are essential for understanding the basic evacuation principles.

3.1 Statement of the Research Problem

The need to strengthen safety precautions and evacuation plans in such cramped areas during flood events is the root of the research problem. The project will investigate how to best utilise evacuation plans, streamline decision-making, and reduce risks for people in underground tube networks by integrating artificial intelligence (AI) techniques into the ABS framework.

3.2 Knowledge Gathering: Evacuation and Safety Measures in Underground Tubes

1. Evacuation Procedures in Underground Tubes:

Underground evacuations, such as those in tube systems, are well-organized to ensure passenger safety. Evacuation plans are tailored to each scenario to reduce anxiety, maintain order, and guide passengers to safety. During the evacuation, passengers should follow emergency signage, cooperate with transit staff, and listen to announcements.

2. Dimensions and Depths of Underground Tubes:

Subterranean tube depths and dimensions vary according to geology, city planning, and available space. The diameter of a subway tunnel usually ranges from 12 to 30 feet, and its depth can be anywhere from a few metres to more than 50 metres below ground.

3. Flooding of Underground Tubes:

Water flow rate, drainage capacity, and flood prevention measures affect how quickly underground tubes flood. Heavy rainfall or overloaded drainage systems can cause rapid flooding. Local conditions can greatly affect flooding timing.

4. Timeframe for Urgent Evacuation in Flooding:

The time for urgent evacuation in a flood depends on water volume, water ingress speed, evacuation efficiency, and exit distance. In cases of rapid flooding, passengers should evacuate immediately per emergency announcements and signage.

5. Individual Responses and Options:

The time for immediate evacuation in a flood depends on water volume, water ingress speed, evacuation efficiency, and exit distance. In cases of rapid flooding, passengers should evacuate immediately per emergency announcements and signage.

1. **Seeking Guidance and Instructions:** People seek emergency guidance from authorities, transit staff, or emergency announcements. To ensure a safe evacuation, they may follow instructions from leaders. Clear, timely information helps passengers respond appropriately.

2. **Emotional Reactions:** Fear, confusion, and anxiety can affect emergency responses. Panicked passengers may act erratically and hinder evacuation. Others can stay calm, follow instructions, and keep order.

3. **Familiarity with the Environment:** Passengers who are familiar with the subway system may help in emergencies. They may know better evacuation routes, exits, and safe spots. Knowing the surroundings can speed up decision-making and improve response.

4. **Split-Second Decision-Making:** People may need to act quickly in changing situations. Some may seek shelter or assistance, while others may move towards exits. Individuals' assessments of the situation and perceived danger can influence these decisions.

5. **Exit Selection and Pathfinding:** Travellers can take the nearest exit or follow the crowd. Choice of exit affects evacuation efficiency and crowd dynamics. People may seek higher ground or follow authorities during a flood.

6. **Obstacles and Challenges:** Evacuations may involve crowded platforms, poor visibility, and unfamiliar surroundings. These obstacles may affect their decision-making and safety progress.

3.3 Analyse Problem

Objectives:

The primary objectives of this project are as follows:

1. **Simulation of Flood Evacuation:** Create a comprehensive ABS framework to accurately simulate underground tube network flood evacuation scenarios. This includes modelling personal movement, floodwater spread, and evacuee interactions.

2. **Enhanced Evacuation Strategies:** Improve evacuation strategies using ABS's AI capabilities. These methods optimise crowd movement, reduce congestion, and maximise evacuation routes.

3. **Decision Support System:** Use integrated model to help emergency responders and authorities make real-time flood evacuation decisions. Simulation data is analysed to make timely evacuation decisions.

4. **Risk Assessment and Mitigation:** Assess flood-related risks and vulnerabilities in underground tube networks. Reduce risks and improve safety for individuals and emergency personnel.

Hypotheses:

The project will examine the following hypotheses:

1. **Optimized Evacuation Plans:** AI-enhanced flood evacuation plans will improve crowd movement and evacuation times.

2. **Enhanced Decision-Making:** The AI-enhanced ABS framework will give emergency responders and authorities real-time data insights to make faster, more informed flood evacuation decisions.

Experimental Factors:

The experimental factors to be considered in this project include:

1. **Evacuation Scenarios:**Simulated flood scenarios will vary in severity, water ingress, and underground tube network bottlenecks.

2. **AI Algorithms:** We will integrate a crowd decision-making AI algorithm into the ABS framework to evaluate evacuation optimisation and decision support.

3. **Evacuee Behaviour:**The simulation will include panic responses, movement preferences, and interaction dynamics during evacuations.

Responses:

The responses to be measured in this project include:

1. **Evacuation Efficiency:** Measure evacuation time, congestion, and route utilisation to assess evacuation plan efficiency.

2. **Decision Support Effectiveness:** Examine emergency responders' simulation decisions for quality and timeliness to evaluate the AI-enhanced decision support system.

3. **Risk Reduction:** Quantify how integrated AI techniques reduce underground tube network risks and vulnerabilities during flood evacuations.

3.4 Define Scope and Key Activities

The scope table facilitates the representation of the necessary inclusions or tasks required to accomplish the objective, while the key activities diagram provides a comprehensive understanding of the interactions and engagements among the agents involved.

Category	Element		ID	Decision	Justification
Actor	Human	Passenger	AC1	Include	Main research subject
		Security Staff	AC3	Include	Guidance to evacuation route
Physical Environment	Service	Speaker	PE0I	Exclude	Guidance to evacuation route provided with trigger
		LED Screen	PE02	Exclude	Guidance to evacuation route provided with trigger
	Structure	Walls and pillers	PE03	Include	Rerquired for motion of passengers
		Door	PE04	Include	Rerquired for motion of passengers
		Stairs / Emergency exits	PE05	Include	Rerquired for motion of passengers
		Ticketing and information area	PE06	Exclude	Not necessary
		Escalators and Lifts	PE07	Exclude	Not necessary since not working under such emergencies
	Weather	Temperature	PE08	Exclude	Not necessary
		Natural light	PE09	Exclude	Indoor environment
	Building	Platform	PE10	Include	Location where passengers move around
		Corridor	PE11	Exclude	Not necessary
		Toilet	PE12	Exclude	Not necessary
Category		Aspect/phenomena	ID	Decision	Justification
Social and psychological Aspects/ Phenomena	Passenger	Movement	spAP01	Include	Part of the simulation to be tested
		Vision area	spAP02	Include	Will affect passengers movement behaviour
	Security Staff	Movement	spAP03	Include	Part of the simulation to be tested
		Vision area	spAP04	Include	Will affect passengers movement behaviour
Category		Detail to be modeled	ID	Decision	Justification
Other		N/A	1	N/A	N/A

Figure 3.1: Scope Table for flood evacuation scenario simulation

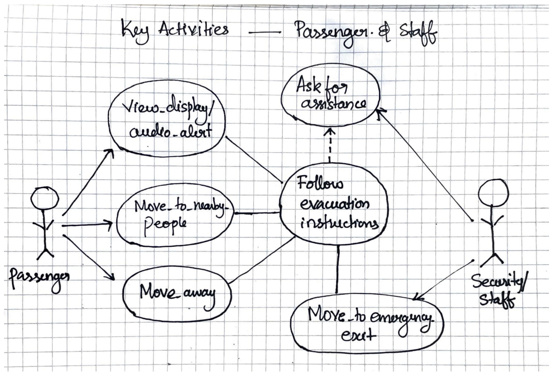

Figure 3.2: Key Activities Diagram

3.5 Archetype Stencils

These allow defining the behavior of actors by using habits/demographics for characterization.

Archetype	Response Time	Walking Speed
Child		
Adult		
Elderly		

Archetype	Total Time for Evacuation
Familiar Passenger	
Non Familiar Passenger	

Figure 3.3: Archetype Stencils

3.6 Agent and Object Stencils

The classes of agents and objects are formally defined. Attributes can be inferred through the utilization of archetype criteria and by examining the scope table. Operations can be inferred from the states depicted in the corresponding state charts that are generated.

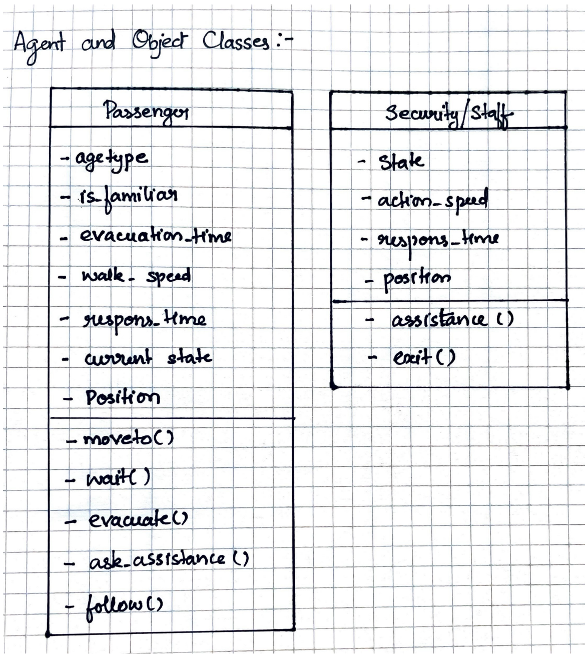

Figure 3.4: Agent and Object Classes

3.7 Interactions

Interactions encompass all components delineated within the Agent and Object Stencils phase. The horizontal axis should include a listing of these elements. The vertical axis can be utilized to enumerate use cases. Alternatively, it is possible to generate distinct diagrams for each specific use case.

3.8 Artificial Lab

Attributes serve as a means of storing information for all agents or objects, as well as the necessary initialization parameters for experimental factors. Operations are intricately connected to the corresponding responses.

3.8.1 Simplifications

Simplifications were made during simulation model design and implementation to ensure feasibility within time and technical constraints. These simplifications simplified the model while maintaining its functionality and research goals.

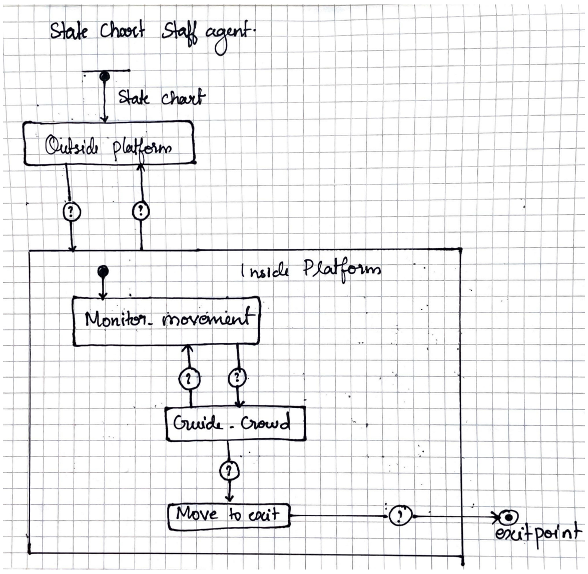

Figure 3.5: Staff State Chart

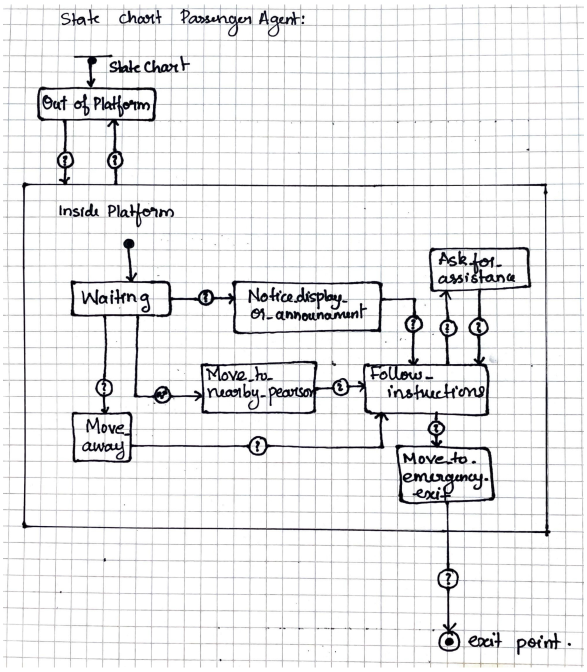

Figure 3.6: Passenger State Chart

From State	To State	Triggered by	When
Outside Platform	Inside Platform	Condition	At arrival. before evacuation warning
Waiting	Notice_display_or_anounce ment	condition	Evacuation alert by speakers or on display.
Waiting	Move_to_nearby_person	timeout	Notice something wrong and tries to find someone nearby.
Waiting	Move_away	timeout	Notice flood water and move away instantly.
Notice_display_or_anou ncement	Follow- instructions	condition	understand the situation and realise where to move to
Move_to_nearby_person	Follow- instructions	condition	understand the situation and realise where to move to along with the other person.
Move away Follow-	Follow- instructions	condition	understand the situation and follow evacuation procedures
Follow- instructions	Ask for assistance	Timeout condition	unable to find exait within prescribed time or is in need of help
Ask for assistance	Follow- instructions	Condition	consulted by a staffed and instructed appropriately
Follow. instructions	Move-to- emergency- excit	Timeout	After following all instruction the passenger evacuates better certain time.

Figure 3.7: Passenger Transition Table

Substitution of Display and Audio Announcements with Triggers

Display screens and audio announcements, common in emergency evacuation scenarios, were replaced with trigger-based events to simplify and optimise computation. The simulation used triggers instead of visual or auditory alerts to start specific actions. This substitution simplified the model while capturing passenger emergency responses.

Utilization of Simplified Archetype Stencils

A simplified archetype stencil was used for implementation to simplify and manage the model. In contrast to the conceptual model, the simulation model used fewer archetypes

From State	To State	Triggered by	When
Outside- Platform	Inside platform	Condition	Evacuation alert
Monitor movement	Guide- crowd	condition	when someone asks for assistance
Guide- crowd	Monitor movement	condition	when all passengers are moving according to instructions
Guide- crowd	Move_to_ exit	condition	when everyone is outsid the exit.

Figure 3.8: Staff Transition Table

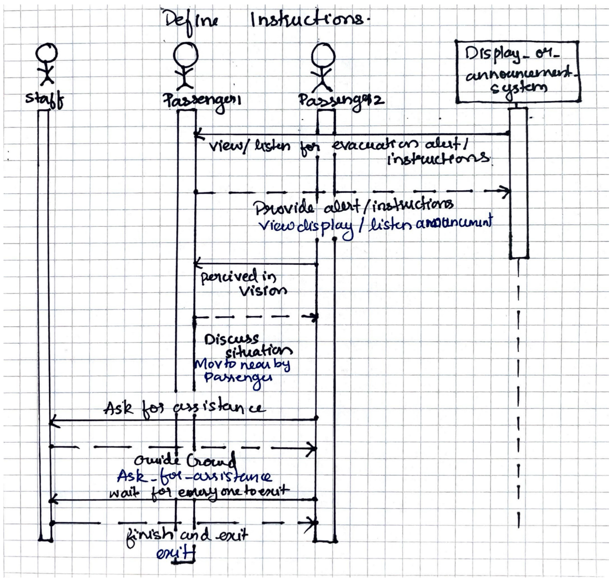

Figure 3.9: Agent-Object Interactions

to represent simplified passenger profiles and behaviours. This simplification kept the model tractable while preserving emergency passenger interactions.

Simplified Responses Compared to the Conceptual Model

The simulation model simplified the required responses compared to the conceptual model. The conceptual model covered many nuanced actions and decision-making processes, but the simulation model captured key responses. This simplification made the model more manageable and efficient without compromising research goals.

Iterative Evaluation Considering Technical Availability

The original model was evaluated in smaller iterations, taking technical constraints and computational resources into account. The simulation remained executable within project constraints with this approach. Iterations allowed incremental improvements and adjustments while balancing model complexity and feasibility.

It is imperative to underscore that although these simplifications were implemented to

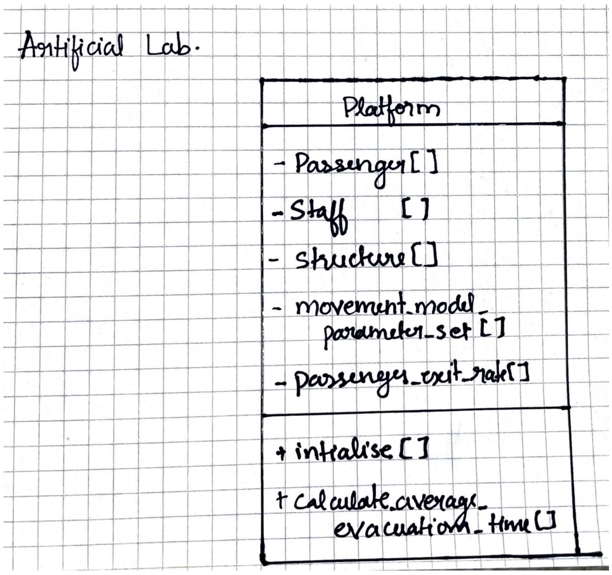

Figure 3.10: Artificial Lab

enhance the feasibility of the simulation, the project successfully accomplished its overarching objective. The development of an Agent-Based Simulation (ABS) framework, which integrates Artificial Intelligence (AI) using the Social Force Model (SFM), establishes a fundamental platform that can be customised and expanded for subsequent undertakings. The decision to simplify certain aspects was made for practical reasons, in order to support the creation of a strong ABS framework that can be used as a solid foundation for more extensive and advanced simulations in the future.

Chapter 4

Implementation

We give a thorough explanation of how our simulation model was put into practise for underground platform flood evacuation in this section. To simulate passenger behaviour during emergency evacuations, the Social Force Model (SFM) is incorporated into the model, which is created using the GAMA modelling platform.

4.0.1 Model Overview

The simulation model, named *UnderGround_Platform_Flood_Simulation*, represents an underground metro station platform during a flooding emergency.The platform itself, tracks, waiting areas, walls, pillars, benches, entry points, stairs, and exit pathways are just a few of the components that make up the platform layout.

The station generates both staff and passengers, who are crucial elements of the simulation. Three types of passengers are distinguished: young people, adults, and the elderly. Each has a distinct response time and speed of movement. The purpose of the simulation is to investigate how passengers leave the platform in an emergency, especially when the water begins to spread.

4.0.2 Social Force Model (SFM)

SFM is based on the principles of physics and psychology and models the forces acting on each individual in the crowd. The key equations used in our implementation are as follows:

- **Repulsion Force:**

$$\vec{F}_{repulsion} = A \cdot \exp\left(\frac{-(r - R)}{B}\right) \cdot \hat{r} \tag{4.1}$$

  where A, B, and R are parameters controlling the strength and range of repulsion, $\vec{F}_{repulsion}$ is the repulsion force, r is the distance between agents, and $\hat{r}$ is the normalized direction vector.

- **Attraction Force (Assistance):**

$$\vec{F}_{attraction} = k \cdot \vec{d} \tag{4.2}$$

  where k is a parameter controlling the attraction strength, and $\vec{d}$ is the vector pointing from the agent to the attracting object (e.g., staff or other passengers).

- **Total Force:**

$$\vec{F}_{total} = \vec{F}_{repulsion} + \vec{F}_{attraction} + \vec{F}_{desired} \tag{4.3}$$

  where $\vec{F}_{desired}$ represents the desired movement direction of the agent.

These equations allow us to model how passengers react to the presence of obstacles, other passengers, and the availability of assistance during an emergency evacuation.

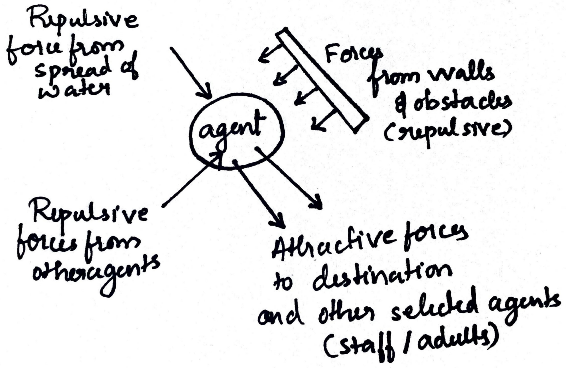

Figure 4.1: Interaction of forces on agent

4.0.3 SFM in Implementation

In our GAMA model, we have integrated SFM to govern passenger movement. Passengers are influenced by repulsion forces from nearby agents, attraction forces towards staff or other adults for assistance, and a desired movement direction. The code snippet shoen in Figure 4.1 demonstrates how the SFM equations are applied in our model

```
loop p over: nearby_passengers {
float ddx <- location.x - p.location.x;
float ddy <- location.y - p.location.y;
float distance <- sqrt((ddx * ddx) + (ddy * ddy));
if distance < 5 and distance != 0 {
repulsion_x <- repulsion_x + (((5 - distance) * ddx) / distance);
repulsion_y <- repulsion_y + (((5 - distance) * ddy) / distance);
    }
}
if (passenger_type = "child" or passenger_type = "elderly") {
    // Attraction to adults and staff for assistance
    list<agent> helpers <- list<agent>((passengers where (each.passenger_type = "adult")) + (staff));
    loop h over: helpers {
        float ddx <- h.location.x - location.x;
        float ddy <- h.location.y - location.y;
        float distance <- sqrt((ddx * ddx) + (ddy * ddy));

        if (distance < 10 and distance != 0) {  // Assuming a larger range for assistance
            attraction_x <- attraction_x + ((10 - distance) * ddx) / distance;
            attraction_y <- attraction_y + ((10 - distance) * ddy) / distance;
        }
    }
}
// Add forces
float move_x <- dx + repulsion_x;
float move_y <- dy + repulsion_y;

// Normalize
float len <- sqrt(move_x * move_x + move_y * move_y);
move_x <- move_x / len;
move_y <- move_y / len;

// Move
location <- {location.x + move_x, location.y + move_y};
```

Figure 4.2: SFM model inplementation

In this code snippet, `repulsion_x` and `repulsion_y` represent the repulsion forces calculated based on the SFM equations. Similarly, `attraction_x` and `attraction_y` represent the attraction forces towards staff or other adults for assistance. These forces collectively influence passenger movement.

4.0.4 Model Behavior

The simulation begins with the creation of passengers and staff members at random locations on the platform. As the simulation progresses, the `start_spreading` trigger simulates flooding after a certain number of cycles. After this trigger, passengers use SFM-based movement logic to reach the emergency exit (Figure 4.2).

When walls block exits, staff can help passengers. Staff help passengers within a certain range reach safety. The simulation counts passengers who have left, are guided, and are active on the platform.

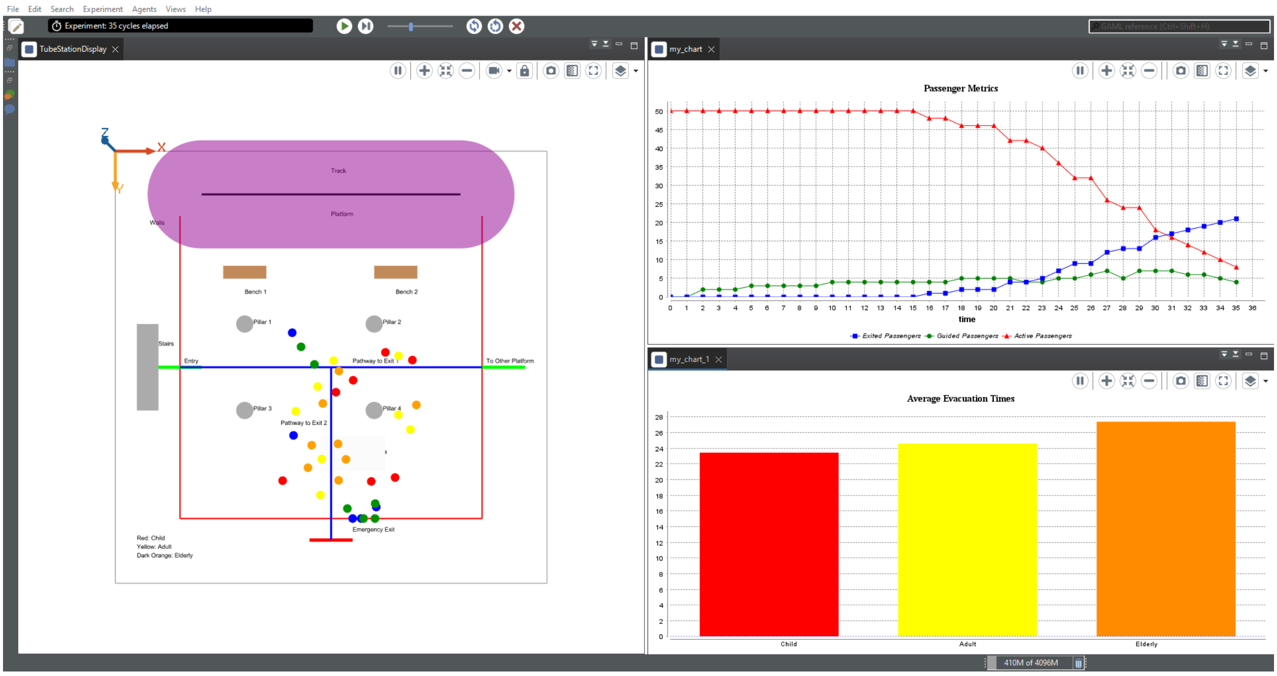

Figure 4.3: Model Implementation

4.0.5 Role of SFM as the AI Component

By mimicking passenger decision-making and movement based on their perception of the surroundings and the impact of outside forces, SFM serves as the AI component in our model. It gives us a realistic picture of how crowds behave during evacuations, allowing us to examine the efficacy of staff members' assistance and evacuation plans.

To put it briefly, our implementation creates a dynamic simulation of underground platform flood evacuations by fusing the modelling capabilities of GAMA with the SFM framework. SFM-based forces control passenger movements, and the model allows us to examine the effectiveness of evacuations and the contribution of assistance to passenger safety.

Chapter 5

Evaluation

In this section, we present the results of our simulation experiments, which aimed to evaluate the sensitivity of the underground platform flood evacuation model and calibrate it for specific evacuation time targets. Due to technical restrictions and for simplicity, we employed small repetitions and batches in our evaluations. The results are visually presented in the figures below.

5.0.1 Sensitivity Analysis

The sensitivity analysis was performed to assess the impact of various parameters on evacuation times. We explored five parameters: Child Speed, Adult Speed, Elderly Speed, Number of Passengers, and Number of Staff. The objective was to understand how changes in these parameters influence the evacuation process.

Evacuation Times vs. Parameter Values

Figure 5.1 illustrates the average evacuation times for different parameter values. Each subplot in the figure corresponds to one of the parameters explored, with its respective range of values.

From Figure 5.1, we can make the following observations:

1. **Child Speed:** Higher child speeds generally lead to shorter evacuation times. Slower children significantly impact evacuation efficiency.

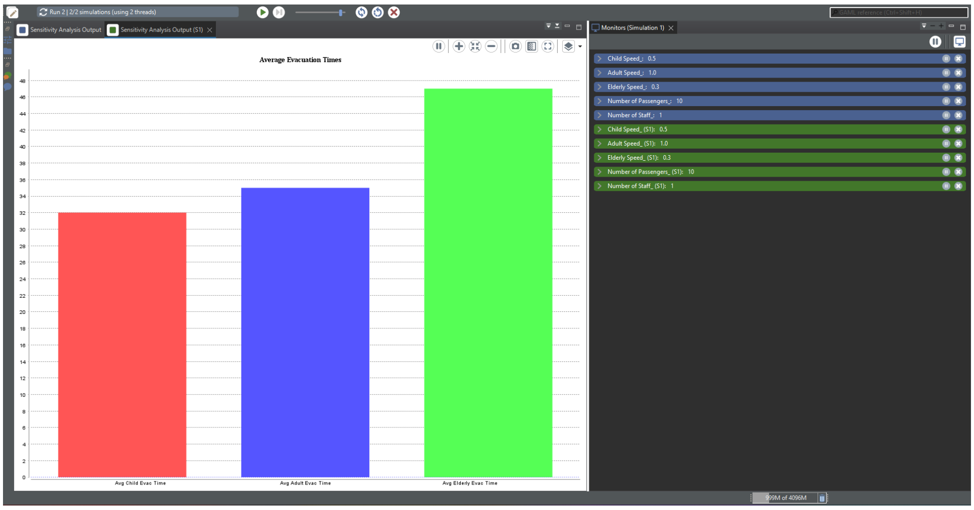

Figure 5.1: Sensitivity Analysis Results

2. **Adult Speed:** Adult speed has a noticeable effect on evacuation times, with faster adults contributing to quicker evacuations.

3. **Elderly Speed:** Speed among the elderly also plays a role; faster elderly passengers contribute to shorter evacuation times.

4. **Number of Passengers:** As expected, an increase in the number of passengers leads to longer evacuation times due to congestion.

5. **Number of Staff:** The presence of more staff members has a positive impact on evacuation times, especially when guiding passengers.

5.0.2 Calibration for Target Evacuation Time

In the calibration process, we aimed to find parameter values that would result in a specific target evacuation time. We used a genetic algorithm to search for optimal parameter combinations. The objective function was set to minimize the absolute difference between the sum of average evacuation times for child, adult, and elderly passengers and the target time (set to 120 time units, and can be changed as needed).

Calibration Results

Figure 5.2 displays the results of the calibration process. Each point in the scatter plot represents a parameter combination. The x-axis represents the sum of average evacuation times for child, adult, and elderly passengers, while the y-axis shows the absolute difference between this sum and the target time.

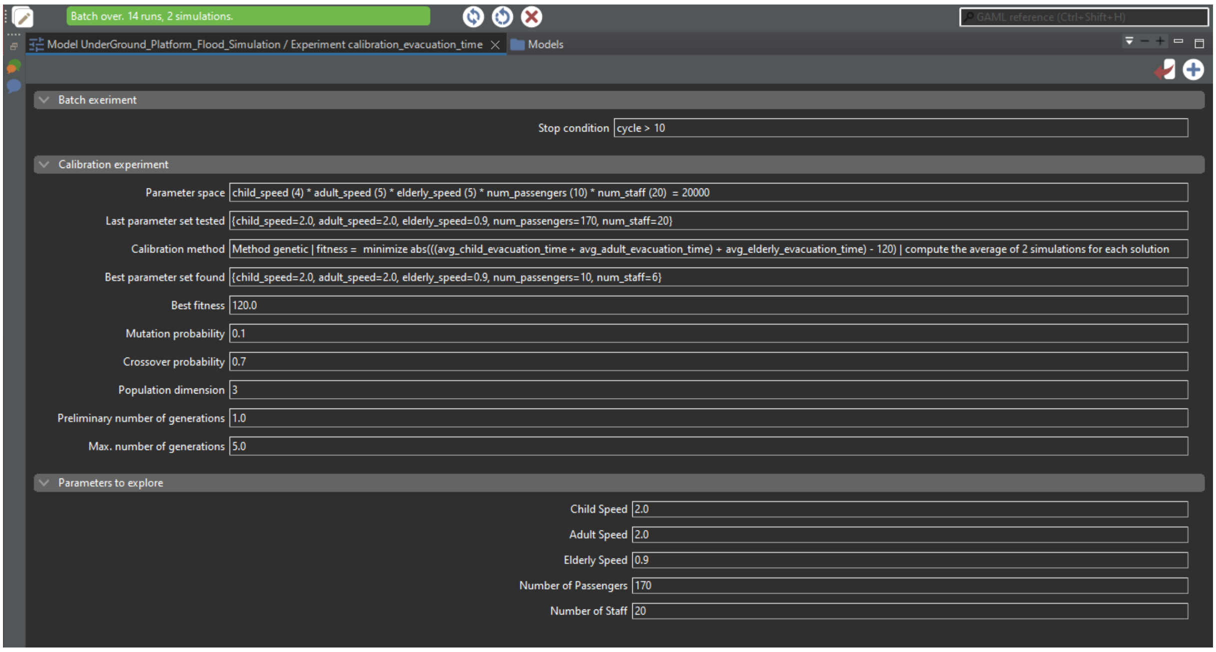

Figure 5.2: Calibration Test Results

From Figure 5.2, we observe that certain parameter combinations resulted in evacuation times very close to the target time of 120 units. This demonstrates the effectiveness of the genetic algorithm in finding suitable parameter values to meet specific evacuation time objectives.

5.0.3 Discussion

The sensitivity analysis revealed the importance of individual parameters on evacuation times, helping us understand how variations in passenger and staff characteristics impact the evacuation process. Faster speeds and a higher number of staff members were found to improve evacuation efficiency, while a higher number of passengers and slower individuals led to longer evacuation times.

The calibration process successfully identified parameter combinations that met the desired target evacuation time. This demonstrates the model's flexibility in adjusting parameters to achieve specific evacuation objectives.

However, it's important to note that the results presented here are based on simplified repetitions and batches due to technical limitations. Further refinements and extended experiments may provide more precise insights into parameter sensitivities and calibration outcomes.

In conclusion, the sensitivity analysis and calibration experiments allowed us to gain valuable insights into the behavior of our underground platform flood evacuation model. We found that parameter adjustments can significantly impact evacuation times, and the calibration process can be employed to meet specific evacuation time objectives. These findings contribute to a better understanding of crowd behavior during emergencies and can inform real-world evacuation strategies.

Chapter 6

Summary and Reflections

6.1 Project Management

Every task and aspect of the work plan was executed with great care throughout this project, ensuring optimal progress and resource allocation. Time and resource management were crucial to project completion.The project was divided into stages: model conceptualization and design, implementation, sensitivity analysis, and calibration. Each phase had a clear timeline and efficient resource allocation. Using a targeted strategy ensured task completion on time. Despite initial implementation challenges, learning and familiarising oneself with GAMA was easier than expected.

Effective resource management was achieved by balancing timeframes to maximise their expertise. The GAMA modelling platform gave the project a resilient and flexible framework based on available resources. Reduced resource waste and improved operational efficiency were attempted. Continuous communication and coordination among team members aligned everyone with project goals, reducing redundant tasks.

6.2 Contributions and Reflections

The project's creativity, innovation, and novelty have contributed greatly. Simulating subterranean flood scenarios with the GAMA modelling platform is the main achievement. The novel approach could revolutionise emergency management and crowd behaviour analysis.

A specialised agent-based simulation model for underground platform flood simulations is one of this project's main contributions. Agent-based modelling has been used in many fields, but underground station flood evacuation scenarios are new. The customised model helps understand emergency passenger behaviour and interactions.

The simulation framework now includes the Social Force Model (SFM), a major improvement. The crowd dynamics-renowned SFM model accurately depicts human behaviour in evacuation scenarios. Our model captures the complex dynamics of passenger movement forces by integrating SFM, improving simulation precision.

This project also shows GAMA's modelling versatility. GAMA is known for simulating complex systems, and subterranean flood scenarios offer new opportunities. The project's success suggests that GAMA could be used to model and analyse emergency situations beyond transportation.

Reflecting on the project's implementation shows that the plan was comprehensive and well-structured. Intricate simulation models and calibration procedures presented challenges throughout the project. The above challenges have illuminated emergency simulation complexity and the need for strong calibration.

After reflection, the project was rewarding. The statement emphasises interdisciplinary collaboration, which integrates knowledge and skills from modelling, computer science, and emergency management. The project's critical evaluation shows that the GAMA-based model can be used to optimise evacuation strategies in various transport hubs and public areas, despite its complexity.The use of GAMA to model flood scenarios in underground platforms advances emergency management and crowd behaviour analysis, enabling future research and exploration. This statement shows how agent-based modelling can accurately simulate complex real-world scenarios.

In conclusion, this project advances emergency evacuation knowledge and methods. The above contribution laid the groundwork for future research and applications in various fields. GAMA's innovation, creativity, and adaptability make it a significant agent-based modelling contribution that could solve urgent social issues.

Bibliography

[1] Balci, O. and Sargent, R.G. (1984). Validation of Simulation Models via Simultaneous Confidence Intervals. *American Journal of Mathematical and Management Sciences*, 4(3-4), pp.375–406. doi:https://doi.org/10.1080/01966324.1984.10737151.

[2] Chen, Y. (2017). Agent-based research on crowd interaction in emergency evacuation. *Cluster Computing*, 23(1), pp.189–202. doi:https://doi.org/10.1007/s10586-017-1134-7.

[3] Edrisi, A., Lahoorpoor, B. and Lovreglio, R. (2021). Simulating metro station evacuation using three agent-based exit choice models. *Case Studies on Transport Policy*, 9(3), pp.1261–1272. doi:https://doi.org/10.1016/j.cstp.2021.06.011.

[4] Gwynne, S., Galea, E.R., Owen, M., Lawrence, P.J. and Filippidis, L. (1999). A review of the methodologies used in the computer simulation of evacuation from the built environment. *Building and Environment*, 34(6), pp.741–749. doi:https://doi.org/10.1016/s0360-1323(98)00057-2.

[5] Li, H., Wang, Y., Jiang, J. and Zhou, R. (2022). Metro station evacuation safety assessment considering emergency response. *SIMULATION*, 98(10), pp.919–931. doi:https://doi.org/10.1177/00375497221095071.

[6] Li, S., Yu, X., Zhang, Y. and Zhai, C. (2018). A numerical simulation strategy on occupant evacuation behaviors and casualty prediction in a building during earthquakes. *Physica A: Statistical Mechanics and its Applications*, 490, pp.1238–1250. doi:https://doi.org/10.1016/j.physa.2017.08.058.

[7] Mandal, T., Rao, K.R. and Tiwari, G. (2022). Simulation of emergency evacuation of passengers with and without disability at different types of metro stations. arXiv:2209.06187 [physics]. [online] Available at: https://arxiv.org/abs/2209.06187 [Accessed 12 May 2023].

[8] Sun, R. and Wu, W. (2022). A Heterogeneous Cellular Automata Model for Crowd Evacuation in Emergency Situations. [online] IEEE Xplore. doi:https://doi.org/10.1109/ITSC55140.2022.9922479.

[9] Taylor, S.J.E., Khan, A., Morse, K.L., Tolk, A., Yilmaz, L., Zander, J. and Mosterman, P.J. (2015). Grand challenges for modeling and simulation: simulation everywhere—from cyberinfrastructure to clouds to citizens. *SIMULATION*, 91(7), pp.648–665. doi:https://doi.org/10.1177/0037549715590594.

[10] www.connectedpapers.com. (n.d.). Connected Papers — Find and explore academic papers. [online] Available at: https://www.connectedpapers.com/about.

[11] Yu, L., Deng, T., Wang, M., Li, Q. and Xu, S. (2018). Passengers' evacuation from a fire train in railway tunnel. *International Journal of Rail Transportation*, 7(3), pp.159–172. doi:https://doi.org/10.1080/23248378.2018.1552210.

[12] Zheng, Y., Li, X.-G., Jia, B. and Jiang, R. (2019). Simulation of pedestrians' evacuation dynamics with underground flood spreading based on cellular automaton. *Simulation Modelling Practice and Theory*, 94, pp.149–161. doi:https://doi.org/10.1016/j.simpat.2019.03.001.

[13] www.cs.nott.ac.uk. (n.d.). The EABSS Toolkit. [online] Available at: https://www.cs.nott.ac.uk/ pszps/eabss2023/ [Accessed 20 Sep. 2023].

[14] Siebers PO and Davidsson P (2015). 'Engineering Agent-Based Social Simulations: An Introduction' (Special Issue Editorial). *Journal of Artificial Societies and Social Simulation*, 18(3). [2018 IF 2.194] [open access link]

[15] Engineering Agent-Based Social Simulations Workshop 2023. [website]

[16] Siebers, O. (2019). Agents to the Rescue: Creating Artificial Labs for Evaluating Human-Centric and Coupled Human-Natural Systems Analyse Problem Knowledge Gathering Case Study Define Scope Define Key Activities Define Archetype Stencils Define Agent/Object Stencils Define Interactions Define Artificial Lab Implement the Model Experiment with the Model How to embed qualitative and quantitative evidence? [online] Available at: http://www.cs.nott.ac.uk/ pszps/docs/pos-Lorentz2019poster.pdf.

[17] References, Siebers, P. and Klügl, F. (2017). Agents to the Rescue: Creating Artificial Labs for Evaluating Human-Centric and Coupled Human-Natural Systems. [online] Available at: http://www.cs.nott.ac.uk/ pszps/docs/pos-Lorentz2019extendedAbstract.pdf

[18] Gomez-Agustina, Luis. (2013). Improvement of voice alarm systems in underground stations. 10.13140/RG.2.1.4567.7846.

[19] A13 -Water Resources and Flood Risk A13.1 -Flood Risk Assessment A13.2 -Water Resources Baseline Report (Mott MacDonald). (n.d.). Available at: https://content.tfl.gov.uk/bscu-twao-envstatement-appendix13-1-floodriskassessment.pdf.

[20] Matters, T. for L. — E.J. (n.d.). Emergency evacuation on the Tube. [online] Transport for London. Available at: https://tfl.gov.uk/travel-information/safety/emergency-evacuation.

[21] Carrington, D. (2016). 57 tube stations at high risk of flooding, says London Underground report. The Guardian. [online] 10 Apr. Available at: https://www.theguardian.com/uk-news/2016/apr/10/57-tube-stations-at-high-risk-of-flooding-says-london-underground-report.

[22] Evacuation procedures for trains, stations and depots. (n.d.). [online] Available at: https://www.whatdotheyknow.com/request/605234/response/1446713/attach/3/05

[23] Transport for London — Every Journey Matters. (n.d.). Available at: https://tfl.gov.uk.

[24] The London Assembly — London City Hall. (n.d.). Available at: https://www.london.gov.uk/about-us/london-assembly.

[25] Tunnel safety — Transport for London. (n.d.). [online] Available at: https://tfl.gov.uk/travel-information/safety/tunnel-safety.

[26] www.london.gov.uk. (n.d.). How London's transport system can become more resilient to flooding. [online] Available at: `https://www.london.gov.uk/sites/default/files/how_londons_transport_system_can_become_more_resilient_to_flooding_report.pdf`.

[27] London's flood risks — London City Hall. (n.d.). Available at: https://www.london.gov.uk/what-we-do/environment/environment-publications/londons-flood-risks.

[28] London Underground: history, facts and figures — Transport for London. (n.d.). Available at: https://tfl.gov.uk/corporate/about-tfl/culture-and-heritage/londons-transport-a-history/london-underground.