Analyzing Emergency Evacuation Strategies for Large Buildings Using Crowd Simulation Framework

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Approval

It is certified that the contents and form of the thesis entitled "Analyzing Emergency Evacuation Strategies for Large Buildings Using Crowd Simulation Framework" submitted by Talha Nadeem has been found satisfactory for the requirement of the degree.

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List of Abbreviations

ABM	Agent-Based Modeling
ANN	Artificial Neural Networks
IoT	Internet of Things
M&S	Modeling and Simulation
PSS	Public Safety & Security
NDMA	National Disaster Management Authority Pakistan
PDMC	Provincial Disaster Management Commission
NIDM	National Institute of Disaster Management

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Abstract

With the ever-increasing advent of man-made or naturally occurring disasters, the safety of individuals is not given the right amount of importance as it should be especially in Pakistan. Focusing on preventative measures for such accidents is one thing but devising and implementing emergency plans in case of such scenarios is just as important. Many precious lives have been lost due to ill planning of emergency evacuations. The occurrence of natural or man-made emergencies can be quite complex and demand flawless preparedness, through tested strategies, in order to ensure the safety of the individuals. For large-scale infrastructures, whether commercial or residential, having a reliable evacuation strategy is crucial. Formulation and evaluation of these evacuation strategies is however a daunting challenge.

A Crowd Simulation and Analysis framework based on bottom-up agent-based modeling and simulation using real-scale building structures has been proposed. A dynamic emergency evacuation simulation model has been developed in which the primary goal being an algorithm proposed to devise the most optimal evacuation strategy for the occupants of a building based on their locations. The individual occupants in the simulation have been modelled as agents enabling us to understand the collective behavior of the agents as a crowd in the simulated environment. Furthermore, the formulation and evaluation of effective evacuation strategies in large buildings is discussed. The functionality of algorithm is demonstrated using a simplistic example and then applied in a campus evacuation case study using three scenarios.

Validation of the proposed algorithm and its performance has also been conducted, the details of which are mentioned later on in the study. The main goal of this research is to assist regulatory authorities in developing effective disaster management plans through the use of M&S methods and tools.

Keywords: *Agent Based Modelling, Crowd Simulation, Emergency Evacuation, Building Evacuation*

Chapter 1 Introduction

This chapter provides the opening and general information of the research to provide a clear understanding about this thesis. It also covers the problem statement along with solution statement.

An emergency evacuation is defined as the immediate act of egress or escaping of pedestrians from an area containing a threat [1]. That area can be an open public gathering place such as stadium or it can be a multistoried building. The scale of an emergency evacuation ranges from small scale evacuations such as the evacuation of a building due to an earthquake, to large scale evacuations such as the evacuation of a city due to flooding. In the case of emergency evacuation of buildings, an evacuation is considered to be complete and optimal once all the occupants of the building have safely exited the building in the shortest possible time based on the scenario. Evacuation plans are devised beforehand and are implemented using different techniques, including evacuation guidelines displayed using sign boards and emergency responders deployed at various locations throughout the building.

There have been thousands of human casualties around the world, all of which point to inadequate planning of emergency evacuations of buildings. Pakistan is ranked amongst the top 10 in the list of countries with the highest number of deaths caused by natural or manmade disasters, which could have been avoided if sound emergency response management and evacuation plans were in place. Emergency evacuations are not just restricted to natural disasters. Manmade disasters also require the quick and timely evacuation of inhabitants which can otherwise result in a large number of casualties [2]. The formulation and implementation of optimal emergency evacuation strategies is of outmost importance in context to the safety of the inhabitants of a building. Accidents can be minimized by preplanning optimal strategies for the building evacuation in the case of both natural and man-made disasters. The damages during emergency situations can be avoided if the organizations are properly trained for the Public Safety & Security (PSS). PSS is usually expressed as a governmental responsibility but can be incorporated within a large organization, or residential societies and primarily aims at prevention and protection of the public from dangers like disasters, health risks, crimes or terrorism. Public Safety refers to the welfare and protection of the general public against natural or man-made disasters and pandemics or environmental hazards whereas Public Security ensures the protection of communities against threats related to crimes, law & order, terrorism and mass incidents (riots). These services bring value to society by creating a stable and secure environment and protection to the people and assets at local, regional and national level. Figure 1: Public Safety and Security overviews different roles of a PSS organization. An effective PSS infrastructure focuses on the timely Monitoring of potential calamities of any kind, mitigate these risks through effective Preparedness and Incidence Response Management.

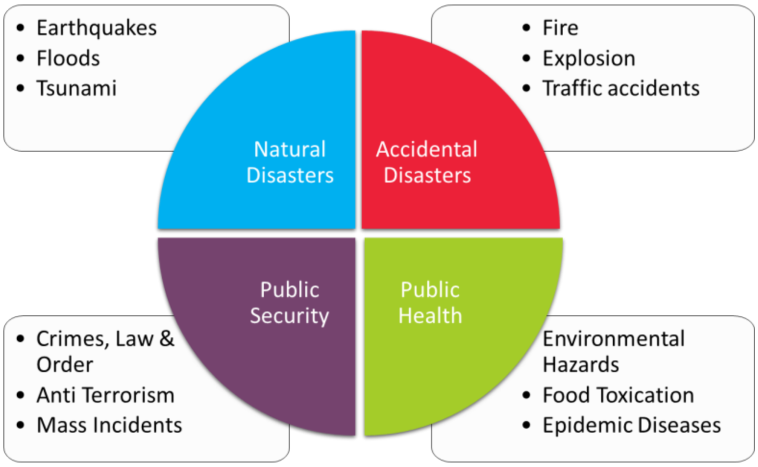


Figure 1: Public Safety and Security

Traditionally, evacuation drills are conducted repeatedly to increase the chances of survival of the regular inhabitants of a particular building. The inhabitants of that building are made aware of the safest and shortest emergency routes of the building which decreases the chances of accidents when subjected to a real emergency evacuation. It is however tedious, disruptive and time consuming to conduct regular emergency drills.

The domain of Modeling and Simulation (M&S) plays a vital role in this regard with many additional benefits. M&S methods and tools provide risk-free and time independent environments which allow effective and thorough analysis, without disrupting the real-world. In many cases, we can't simply afford to find the right solutions by experimenting with the real world. Experimenting or making changes in the real world may be too expensive, dangerous, or just impossible. It is therefore quite challenging to experiment emergency scenarios in real environments and to formulate the evacuation plans for public safety. On the contrary, simulation models are low cost, time independent and offer a harmless experimental environment, thus becoming useful in replicating real scenarios in the risk-free world, where modelers can perform different experiments to gain the insights of the system and compare different strategies to determine the optimal solutions. Modeling allows for the implementation of a real-world system into a risk-free world for the purpose of studying the system in detail, gain insights, compare various alternatives or conditions to study the behavior of the real-world system. With the increased accessibility of abundant computational power, M&S domain has encompassed almost all the industrial domains, and has specially proven to be valuable in the domain of emergency disaster management.

Evacuation modeling purposefully abstracts and simplifies the pedestrians as entities, their individual as well as collective behaviors within walled structures, activities, and their responses to different possible scenarios within large building structures. Crowd Simulation focuses on the execution of multi-scenario evacuation strategies using all available exits, identifying and overcoming possible bottleneck areas in the building, emergence of unforeseen behavior of the crowd as a whole and much more. Crowd Simulation approaches have gained renewed interest of the communities to model and simulate different scenarios and replicate fire breakouts, earth quakes, or insurgency attacks in a building. Optimal evacuation plans can be devised and tested exhaustively, before they are implemented in the real-world. There are numerous modelling paradigms which can be used for the purpose of crowd simulation [3]. These are mainly categorized into Macro, Meso and Micro scale depending on the crowd size and the granularity of the structures and the behavior of the modeled elements [4]. Crowd simulation has been effective in modeling and analyzing behavior and movements of dense crowds in different areas such as: shopping malls, airports, stadiums and parks, therefore can help in adapting better strategies to manage the crowd and reduce causalities. Incidents in largely crowded events are worsened due to key contributing factors including: high densities above 7 or 8 persons per square meter, complex motion flows, stampedes, lack of emergency evacuation structures, untrained mob and slow in-time rescue. With the help of a simulated evacuation model, crucial factors that are hidden or overseen in real life scenarios can be identified through the emergent behavior and interaction of the modeled agents.

In this research, a Crowd Simulation and Analysis framework is proposed for the emergency evacuation modeling, simulation, visualization, analysis and the optimization of large buildings, using real-scale building structures coupled with agent-based approach. Furthermore, an algorithm called: Nearest Exit Shortest Time (NEST) is proposed, in order to devise an evacuation strategy, that not only assigns exits to different regions based on shortest distances but also load balances the crowd at the different exits by using different time windows. The functionality of the algorithm is demonstrated using a simplistic example and applied in a campus evacuation case study using three scenarios. The algorithm outperforms random evacuation and scales up when the population is increased. The main goal of this research is to assist regulatory authorities, and PSS organizations at local, regional or national level, in devising effective disaster management plans through the use of M&S methods and tools.

1.1 Challenge

The lack of preparedness for emergency evacuation situations can prove to be fatal for thousands of individuals if proper planning and implementation of emergency evacuations isn't made beforehand. Pakistan is in the Top 10 list of countries with the highest number of deaths caused by natural and man-made disasters [5]. The public bodies deployed to ensure the safety/emergency regulations are not actively ensuring the safety of individuals in the domain of building evacuations. Emergency evacuations are the most basic preventative measure for the safety of individuals inside a building. Hundreds and thousands of precious lives are at stake when no importance of given to this domain of public safety. Putting the safety of individuals at priority, optimal evacuation plans are a crucial part of public safety. They should be thoroughly tested and verified before ensuring the implementation of such measures. Therefore, it is necessary to devise measures or systems that can aid in the selection of the best/optimal emergency evacuation plan for a given building.

1.2 Problem Statement

Emergency evacuation plans that have been thoroughly tested and verified are needed to be developed in order to increase the safety and security of the inhabitants of a building. There is a need to develop a simulation framework that models the evacuation dynamics of humans and their response/behavior when faced with obstacles during an emergency evacuation e.g. interactions with irregular arrangements of walls and doors in a walled structure. This will lead to the analysis of key factors affecting the complete and optimal evacuation of a building. A simulation framework that incorporates the building layer coupled with pedestrian dynamics will enable us to identify the limitations in the current evacuation methods/models deployed in buildings. This will further provide insights that will fuel the decisions for a better emergency evacuation approach.

1.3 Solution Statement

An optimal emergency building evacuation algorithm is proposed with the help of modelling and simulation framework. The mentioned framework provides decision support and strategies by the modeling and simulation of different scenarios encountered in a building evacuation. These important findings then aid in the fine tuning and development of the proposed algorithm which assists in the complete and quick evacuation of a building.

1.4 Key Contributions

With the help of the proposed algorithm combined with the agent-based modelling framework, the inhabitants of a building will be able to (i) evacuate the subject building in the shortest possible time while (ii) avoiding the buildup of congestion and blockages at the available exits. PSS organizations will be able to (iii) utilize our proposed algorithm for the devising of optimal evacuation strategies for different types of buildings which will (iv) increase the public safety of individuals and (v) prevent the occurrence of large number of casualties in emergency scenarios.

1.5 Research Impact

The proposed algorithm provides the optimal emergency evacuation strategy for a given building. This will help decision makers to preplan the safest and quickest evacuation strategy so that the maximum number of lives are saved in the event of a manmade or natural emergency. This agent-based modeling of emergency evacuation coupled with building layer will allow the modelling of different buildings and scenarios to determine optimal evacuation strategies.

1.6 Related Industry

The proposed algorithm provides appropriate solution to both private and governmental organizations that involve in emergency building evacuation planning and policymaking. They include:

- National Disaster Management Authority (NDMA)
- Provincial Disaster Management Commission (PDMC)
- The United Nations and its organizations
- The International Federation of Red Cross and Red Crescent Societies
- International non-governmental agencies

1.7 Model of Study

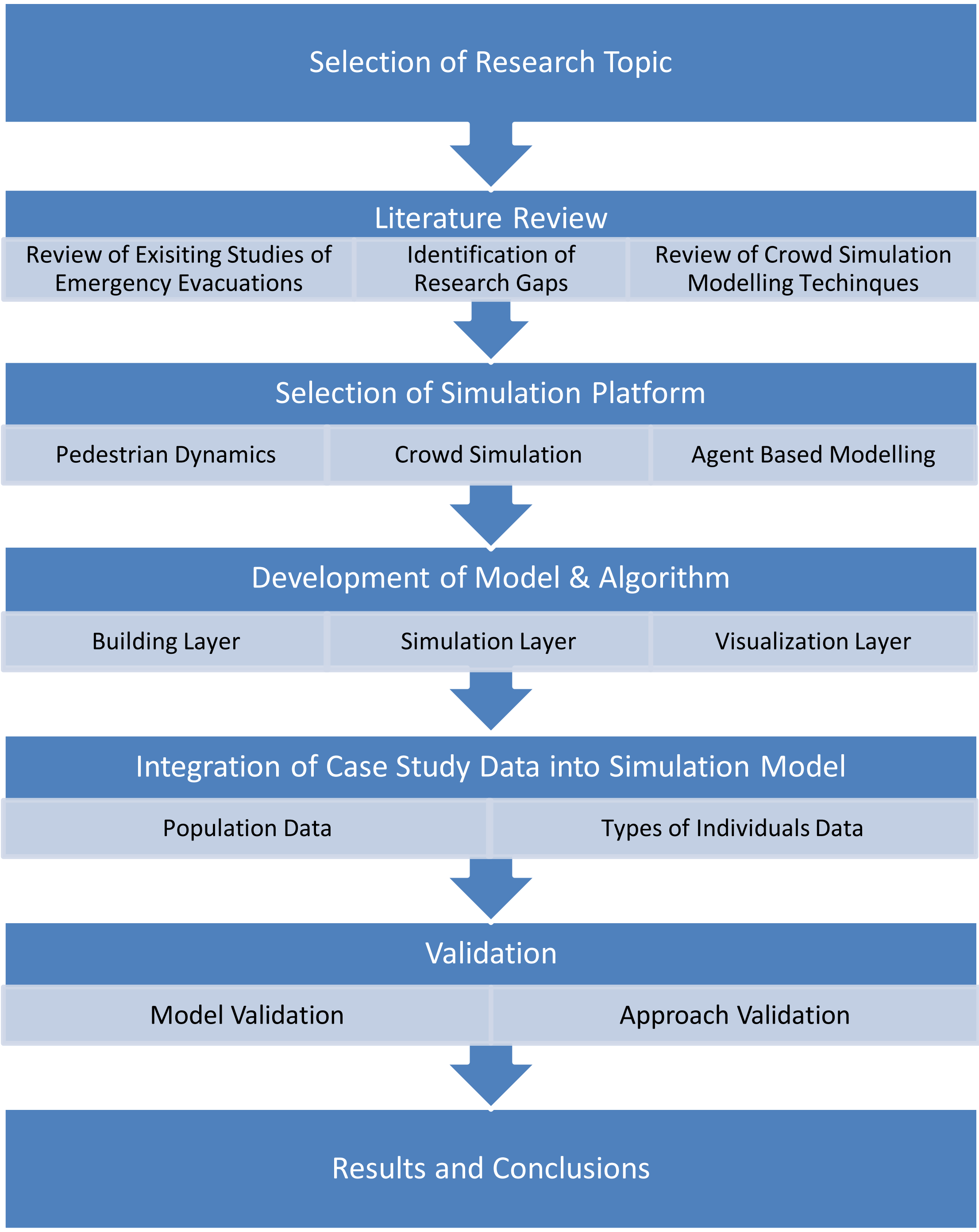


Figure 2: Model of Study

1.8 Thesis Organization

Rest of the thesis is organized into the following chapters:

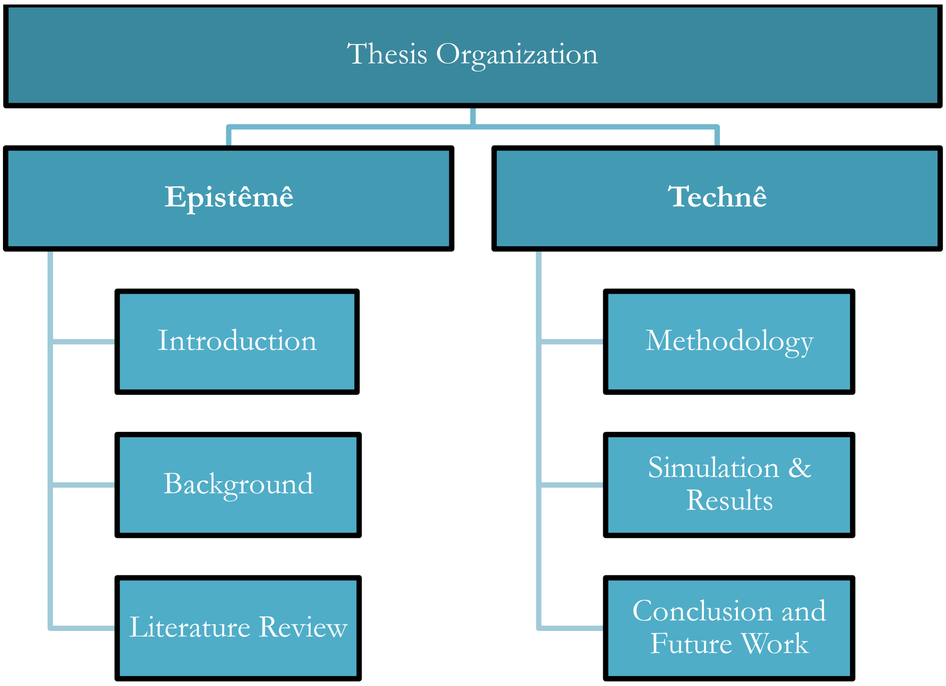


Figure 3: Thesis Organization

1.8.1 Chapter 2: Background

Chapter 2 provides brief overview of Emergency Evacuations and its types. This chapter also explains current facts and figures caused due to inadequate emergency planning in Pakistan followed by the basic concepts of crowd simulations and also a brief introduction of AnyLogic Simulation software.

1.8.2 Chapter 3: Literature Review

This chapter explains the work done so far related to crowd simulation approaches, pedestrian dynamics and building emergency evacuation techniques. It also provides a table of the literature used in this study followed by the position of this thesis in the state of the art.

1.8.3 Chapter 4: Methodology

Modeling and simulation of emergency building evacuation is carried out using AnyLogic simulation Software. Brief introduction to the simulation framework is provided in this section along with detailed explanation of the proposed algorithm and its details. Furthermore, the working and implementation of the proposed algorithm is also explained in detail.

1.8.4 Chapter 5: Simulation and Results

This chapter is dedicated to the demonstration of the functionality and results of our proposed algorithm using a case study. The proposed algorithm is validated with existing models. The chapter is further concluded by the obtained simulation results and their discussion.

1.8.5 Chapter 6: Conclusion and Future work

Brief summary of the thesis research work is presented in this section provided with tasks that can be carried out later for further research studies.

Chapter 2 Background

This chapter provides a brief overview of Emergency Evacuations, its types and facts and figures related to Pakistan followed by an overview of crowd simulations.

2.1 Emergency Evacuations

The act of abrupt egress/escaping of people from an area is known as an emergency evacuation [6]. Emergency evacuations are executed to ensure the safety of individuals from any form of danger or threat in a specified area. That area of evacuation can be a public gathering area such as a stadium or a concert venue; it can also be a multistoried building. Based on the type of emergency evacuation being conducted, there are two categories of emergency evacuations.

2.1.1 Small Scale Emergency Evacuations

Small scale emergency evacuations are mostly building evacuations which occur due to a possible fire breakout, a terrorist attack, or any other reason which can invoke the danger of the occupants of that building [6].

2.1.2 Large Scale Emergency Evacuations

Large scale emergency evacuations are those mass evacuations that are implemented on a city or regional level. The reasons for these evacuations can be flooding, earthquake, forest fires, etc. [6].

2.1.3 Optimal Evacuation

Amongst the different scales of evacuations, there is one common important attribute among them. Regardless of how large or small the emergency evacuation is, the integrity of the evacuation strategy is based on how optimal the evacuation really is. In the case of emergency evacuation of buildings, an evacuation is considered to be complete and optimal once all the occupants of the building have safely exited the building in the shortest possible time based on the scenario [7]. Both the aforementioned constraints have to be fulfilled in order for an implemented evacuation strategy to be considered optimal and complete. A brief summary of the recent earthquakes that occurred in Pakistan can be seen from **Error! Reference source not found.**.

Date	Locality, district, or province	Magnitude (Mw)	Deaths	Injuries
08/10/2005	Azad Kashmir, Balakot	7.6	86,000–87,351	69,000–75,266
24/09/2013	Awaran District, Balochistan	7.7	825	700
28/09/2013	Awaran District, Balochistan	6.8	400	530
26/10/2015	Badakhshan Province	7.5	399	2536
25/12/2015	Gilgit-Baltistan Khyber Pakhtunkhwa	6.3	4	100
18/01/2011	Dalbandin, Balochistan	7.2	3	some
08/05/2014	Sindh	4.5	2	50
31/01/2018	Badakhshan Province	6.1	1	11

Table 1: Earthquakes in Pakistan from 2005 – 2018

2.2 Crowd Simulation

The process in which the dynamics and movements of a huge number of pedestrians are simulated is known as crowd simulation [8]. Crowd Simulation is used by a wide range of industries in order to easily understand the crowd dynamics in a given area/region with the help of simulation tools. Crowd simulation tools help in time saving analysis of unforeseen circumstances that arise due to the collective behavior of a large number of individuals or entities. These analyses obtained from crowd simulations later on aid in urban planning, evacuation planning and even military simulations.

2.2.1 Crowd Simulation Approaches

Various crowd simulation tools and approaches exist for the purpose of simulation the behavior of different types of crowds in various conditions. Some approaches only focus on the macroscopic behavior of the crowd [9]. If the modeler wants to incorporate global and social laws into the simulated model, entity-based approach can be used [10]. A third type of approach, Agent-based approach, allows for the modeling and simulation of autonomous individuals placed together in an interact able environment. Individual pedestrians that are modeled with the help of this approach have the ability to communicate with each other based on a set of predefined guidelines. These simulated pedestrian or agents can also respond and make decisions based on the current situation. Modelers have the complete freedom of simulating various types of behaviors and attributes of the modeled agents using agent-based approach [11].

2.3 AnyLogic

AnyLogic [12] is a multipurpose modeling and simulation tool that comes with a graphical user interface which allows the modeler to quickly model complex environments. AnyLogic Simulation environment provides both a user-friendly Integrated Development Environment (IDE) as well as an efficient simulation engine that allows the modelers to quickly create and simulate high fidelity models of complex systems. It supports different modelling techniques such as Discrete Event, Agent Based and System Dynamics. We can develop complex hybrid models with the combination of discrete event, agent-based and system dynamics. AnyLogic provides user-friendly interface, Java-based development environment and a set of multipurpose component libraries, which all together help to robust the modelling process. The Space markup library within AnyLogic offers the necessary elements required for recreating a scaled graphical model of the spatial environment in which the agents will reside within the model. Its different primitive elements such as, walls, polylines and pathways can help to make floor plans. Next, the modeler can create a logical flow of the pedestrians using the built-in Pedestrian library. The pedestrians are represented as agents with their physical and behavioral characteristics ranging from size (diameter of an average male or female), age, weight, height and gender, normal or handicapped etc. Based on the selected model resolution, the modeler may choose to incorporate these microscopic details in the model given that the tradeoff between the level of details and the execution performance is taken into account. In this research we are using AnyLogic simulation software for the development of proposed framework. Its rich features help us to build complex simulations robustly. We can design custom agents in AnyLogic using agent-based paradigm whereas other simulation tools don't provide the capability of using agent-based modeling approach [4].

2.3.1 Pedestrian Dynamics

The AnyLogic pedestrian library is one of the many built-in libraries provided by the AnyLogic developers [13]. This library was designed to incorporate real pedestrian dynamics in the AnyLogic simulation environment. This library aids modelers by allowing them to visualize, analyze and accurately model the crowd flow behavior in a physical environment. With this level of support provided by the software, the simulation model can be optimized to a higher resolution, resulting in more realistic and accurate simulations.

With the help of the pedestrian library, the modelled agents interact with the simulation based on physics rules such as avoiding walls and avoiding collisions with other agents. Other than just helping in developing the model, the library also provides tools to analyze the developed model so that results can be easily obtained pertaining to the domain of pedestrian dynamics. Density maps, pedestrian counters, and pedestrian flows are some of the many analysis tools offered by this library.

The modeling blocks provided by this library enable a smooth and quick model development process [13]. Designated pedestrian blocks offer detailed control of the agents at each stage of the model.

Chapter 3 Literature Review

This chapter documents the modeling of Emergency Evacuations, Pedestrian Dynamics and Crowd Simulation approaches provided in the existing literature. Moreover, it contributes to understand development in the area of research.

3.1 Area of Research

A detailed literature review has been conducted to identify studies related to existing emergency evacuation techniques and simulation methods. Studies show that there are multiple techniques available for the purpose of modeling and simulation of crowd evacuations. The core difference amongst the available techniques lies in the main goal being targeted to be achieved through the modeling and simulation. The provided literature review is divided into the following sub-sections as shown in Figure 4: Areas of Research.

Figure 4: Areas of Research

Table 2 summarizes the literature work in the sequence of division shown in Figure 4: Areas of Research whereas details of these papers are described later.

Crowd Simulation Approaches		
Author(s)	**Paper Description**	**Key Features**
N. Wagner and V. Agrawal [14]	Implemented an agent-based model to address preparedness and planning.	• Agent based modeling framework • Addressed preparedness and planning in case of fire disasters • Real time simulations
D. Chen, G. S. H. Tan, A. Fagette, and S. Chai [15]	Proposed a real time agent-based simulation framework, based on live position tracking from a surveillance video.	• Real time Crowd Simulation based on agent-based simulation framework • Live position tracking from surveillance video • Algorithm is proposed to solve missing human positions in video frames and generate optical flow of human moving patterns based on density estimation.
M. Zhao, J. Zhong, and W. Cai [16]	Introduced roles of leaders and followers to model human behavior in high density crowds.	• Role-dependent (RD) data-driven crowd modeling approach. • Introduced roles of leaders and followers to model human behavior • Data driven model to simulate the collective behavior of crowd (lane formation) • Incorporates optimization strategies in evacuation process to improve efficiency of evacuation. • Utilized Validation criteria
N. Hu, J. Zhong, J. T. Zhou, S. Zhou, W. Cai, and C. Monterola [17]	Proposes a framework to optimize crowd evacuation using a feedback system based on genetic programming.	• Proposed a framework to optimize crowd evacuation using a feedback system based on genetic programming. • The approach shows a shorter evacuation time and reduced congestion. • Approach validated through video surveillance • Delay concept was introduced to minimize the overcrowding.
A. Abdelghany, H.	Emerging behavior of lane formation and	• Cellular Automata Framework

Mahmassani, K. Abdelghany, H. Al-Ahmadi, and W. Alhalabi [18]	shock-rare faction waves on encountering hurdles is observed.	• Simulation-based study to evaluate incidents in pedestrian/crowd tunnels and similar elongated confined facilities. • lane formation and shock-rare faction waves on encountering hurdles is observed. • flow dynamics of pedestrians show a very similar behavior to that of vehicular flow
I. Mahmood, M. Haris, and H. Sarjoughian [4]	Different evacuation strategies are analyzed to find out the minimum evacuation time.	• Crowd Simulation based on agent-based simulation framework. • Optimized agent based real-scale approach, implemented in AnyLogic to model and analyze complex crowd behavior. • 3 different evacuation strategies are analyzed to find out the minimum evacuation time. • Use of AnyLogic for simulation framework.
M. Haris, I. Mahmood, M. Badar, and M. S. Q. Alvi [7]	Ensures the quick and safe evacuation using optimization techniques and route divergence in case of blockage.	• Real time Crowd Simulation based on agent-based simulation framework • Use of optimization techniques and route divergence in case of blockage. • Harmony Search Algorithm • Shortest Distance Evacuation • Re-routing of Emergency evacuation path in case of exit/route blockage
Pedestrian Dynamics and Crowd Behavior		
Author(s)	**Paper Description**	**Key Features**
A. Tordeux, G. Lämmel, F. S. Hänseler, and B. Steffen [19]	Simulated pedestrian dynamics at a mesoscopic scale, allowing more granularity and faster simulation of large-scale crowds.	• Planned pedestrian flow model is one few mesoscopic models • defines pedestrian dynamics in 2 dimensions • Fundamentally replicates stochasticity in relations of distinct walking patterns • Uses lesser computational costs

J. Wang, L. Zhang, Q. Shi, P. Yang, and X. Hu [20]	Presented a multi agent framework incorporating the individual decision making in a panicked state.	• Agent based congestion evacuation model. • Incorporated the behavior and capabilities of agents to aid in agent decision making. • Comparison between panic and no-panic conditions (amongst agents) and addition of virtual leader during evacuation. • Positive effect of introduction of virtual leader in simulation. • Results show that when in panic, agents ignore alternate pathways.
F. Qiu and X. Hu [21]	Different group sizes, intragroup structures and inter-group relationships can have significant impacts on crowd behaviors.	• Provides a combined framework for modeling several intra-group structures relationships. • Executed in an agent-based crowd simulation model. • Developed framework allows various clustered structures to be modeled.
D. Zhou et al. [22]	Implemented a cellular automaton model to study pedestrian evacuation based on a real experiment.	• Model outlines the design calculation of pedestrian probability based on floor field and queue length • Evacuation plan that highlights the queuing outcome helps lessen the quantity of pedestrian in queue
X. Lu, Z. Yang, G. P. Cimellaro, and Z. Xu [23]	Applied a social force model for areas of high risk in case of an earthquake.	• Danger zones of dropping debris is forecasted • Effect of debris on pedestrian movement is also measured.
Building Evacuation		
Author(s)	**Paper Description**	**Key Features**
A. Khan, A. A. Aesha, J. S. Aka, S. M. F. Rahman, and M. J. U. Rahman [24]	Developed an Internet of Things (IoT) kit that individuals wear and are guided to the nearest exit in case of Fire.	• Wearable IoT device • Guides wearer away from heat zones and towards nearest exit • Uses A* search algorithm • Accommodates for Congestions
U. Atila, Y. Ortakci, K.	Developed a user-specific mobile	• User-Specific Application

Ozacar, E. Demiral, and I. Karas [25]	application for the purpose of evacuation in case of fire breakout.	• Route formulation Based on ANN • Incorporates User Health and condition to better facilitate in evacuations
W. Dong, C. Yu, and M. Zhibin [26]	Discuss the prospect of directional sound for the purpose of evacuation	• Sound Based evacuation • Use of directional speakers • Wide application range.
M. Hoshino, M. Ito, and K. Sezaki [27]	Use of Bluetooth based flow monitoring in case of evacuation	• Use of Bluetooth to monitor flow of evacuees • Real-time route providence to avoid congestion in dense areas
L. W. Chen, J. H. Cheng, and Y. C. Tseng [28]	Use of wireless sensor networks for congestion avoidance	• Wireless sensor networks used to minimize extreme densities and congestions

Table 2: Literature Review

3.2 Crowd Simulation Approaches

Agent based approach has been widely used in literature to study the emerging behavior of crowds. Wagner and Agrawal implemented an agent-based model to address preparedness and planning in case of fire disasters in a mass gathering such as concerts [14]. The Model allows for customization of concert venue layout and testing of different scenarios. Real time simulations combined with agent based are used to study and predict the emerging behavior of the crowd with more accuracy. However, the implementation of the study is limited to concert venues e.g. stadiums and auditoriums.

Chen et al. proposed a real time agent-based simulation framework, based on live position tracking from a surveillance video [15]. An algorithm is proposed to solve the challenge of missing human positions in video frames, and to generate optical flow of human moving patterns based on density estimation. The proposed algorithm is focused on the corrective measures for the real time crowd simulations.

Another approach to study crowd behavior involves assigning different roles to entities in a crowd. Zhao et al. introduced roles of leaders and followers to model human behavior in high density crowds [16]. This data driven model is able to simulate the collective behavior of crowd such as lane formation in a realistic way. However, this study does not incorporate the case of emergency evacuations. Incorporating optimization strategies in evacuation process improves the efficiency of process. Hu et al. proposes a framework to optimize crowd evacuation using a feedback system based on genetic programming [17]. This approach shows a shorter evacuation time and reduced congestion but it is applicable only to scenarios flexible enough to allow intervention in evacuation planning and moving speed. This is only possible in scenarios where there is enough flexibility to allow for interventions in on-going evacuations and the pedestrian moving speeds.

Emerging behavior of lane formation and shock-rare faction waves on encountering hurdles is observed and the dynamics were studied by Abdelghany et al. [18]. The flow of pedestrians in a crowded tunnel was simulated using micro-simulation model and cellular automata. Their findings show that in a high-volume elongated area like a tunnel, flow dynamics of pedestrians show a very similar behavior to that of vehicular flow. The scope of this study is limited only to elongated facilities where lane formation is more likely to occur among pedestrians.

In the event of mass gatherings such as Hajj, different evacuation strategies are suggested to control the crowd flow. Mahmood et al presented an optimized agent based real-scale approach, implemented in AnyLogic to model and analyze complex crowd behavior, in which different evacuation strategies are analyzed to find out the minimum evacuation time [4]. In this study, the optimization approach is limited to open areas that do not involve structural dynamics e.g. walls and rooms. Another large-scale agent-based emergency evacuation model is proposed by Haris, et al in AnyLogic that ensures the quick and safe evacuation using optimization techniques and route divergence in case of blockage [7]. Harmony search and shortest distance algorithms are used to find out the best evacuation path. Results show that adopting a safety mechanism reduces the overall evacuation time.

3.3 Pedestrian Dynamics and Crowd Behavior

Understanding of crowd behavior and the pedestrian dynamics has its application in modeling the evacuation of large buildings and areas. Pedestrian dynamics contribute in the expansion of crowd collective behavior. Tordeux, et al. simulated pedestrian dynamics at a mesoscopic scale, allowing more granularity and faster simulation of large scale crowds [19].

Modeling the panic state in agent behavior is more likely to reproduce the real-world evacuation process. Wang et al. presented a multi agent framework incorporating the individual decision making in a panicked state [20]. Simulation results show that when in panic, agents tend to choose the crowded exits ignoring the alternate pathways. This implementation doesn't incorporate the de-congestion of pedestrians through balancing of assigned exits. Introducing the role of a virtual leader in agents has shown great improvements in the efficiency of evacuation. The work of Qiu and Hu models the grouping phenomenon in pedestrian crowds, and shows that the different group sizes, intragroup structures and inter-group relationships can have significant impacts on crowd behaviors [21]. Their work doesn't cover the evacuation of large groups or crowds.

Queuing behavior plays an important role in the efficiency of crowd evacuation. Zhou, et al. implemented a cellular automaton model to study pedestrian evacuation based on a real experiment [22]. Focus of queuing behavior in crowd simulation has contribution in reduced pedestrians waiting in queue and shorter evacuation times. But in general, queuing leads to the creation of congestions which we are targeting to reduce in our study.

Earthquake evacuation modeling has shown that the distribution of falling debris results in an increase of hurdles in evacuation flow. Lu, et al. has applied a social force model for areas of high risk in case of an earthquake [23]. This model is useful in future urban planning. Results show that falling debris affect the evacuation time and the efficiency of an evacuation in a negative way.

3.4 Building Evacuation

There are many methods and strategies for the purpose of evacuation of buildings in general. The key difference that lies in these methods is where the method is applicable and for what scenario is the method best suitable for. For example, if we consider the situation in which the building or a portion of the building has caught on fire. The main hurdle to overcome in a fire situation is the visibility issue. Due to the dense smoke generated by burning of different materials in the building, it becomes very difficult to navigate to safety inside the building. One research team developed an Internet of Things (IoT) kit that individuals wear and are guided to the nearest exit [24]. Their wearable hardware module communicates with the software server which guides the wearer away from heat intensive zones and towards the nearest exit. The nearest exit is calculated based on A* Search algorithm. Similarly, another team developed a user-specific mobile application for the same purpose of evacuation in case of fire breakout [25]. Their mobile application accommodates the physical and mental conditions of the user to better facilitate in the exit path formulation. The optimal route is decided with the help of Artificial Neural Networks (ANN).

In order to tackle the difficulty of evacuation from a visually difficult environment, directional sound based method also exists [26]. The research team tested directional sound navigation amongst a group of people from different age groups and concluded that evacuation a building with the help of sound-based navigation is possible. Although the placement of the directional speakers in an actual environment requires further research.

Another approach for building evacuation utilizes Bluetooth devices for the detection and navigation of individuals during an evacuation [27]. By utilizing the Bluetooth sensors in the mobile phones of the individuals, the densities of the evacuees can be identified and labelled as congestion areas. The route provided by the Bluetooth based evacuation system will incorporate the avoidance of such dense areas to aid in the quick evacuation of the individuals in danger and provide real-time direction guidance for the purpose of evacuation. Similarly, another wireless sensor based evacuation guidance system is proposed which aims at load-balancing the individuals to avoid unnecessary congestion inside the building [28].

3.5 Position of the thesis

The various relevant studies discussed in the literature reviewed above provide many different approaches combined with optimization techniques to enable the optimal evacuation plan for a building. Each study focuses on its own approach and method. The goal of this study is to combine all three sections, i.e. crowd simulation approaches, pedestrian dynamics and building evacuation to generate an optimal evacuation approach/algorithm that caters for de-congestion at the exit paths during evacuation by balancing the available exits of the building. The discussed approaches lack this feature as well as the utilization of time windows which our proposed algorithm, Nearest Exit Shortest Time (NEST), is catering for. The shortest distances which are calculated by the algorithm are GIS based distances because the model has been developed on a scaled architectural layout of the actual building. The details of the implementation of the algorithm can be found in Chapter 4.

Chapter 4 Methodology

In this chapter we first discuss the proposed Crowd Simulation Framework and then propose an evacuation optimization Algorithm based on agent-based crowd simulation and analysis framework.

4.1 Crowd Simulation & Analysis Framework

In this section we discuss our proposed Emergency Evacuation Simulation & Analysis framework, which is capable of: (i) modeling buildings using complex spatial structures and the pedestrian dynamics; (ii) Simulating large crowd flows in the buildings using different scenarios; and (iii) evaluating different evacuation strategies. This helps in creating an adequate evacuation plan or evaluating an existing plan for effectiveness. It is composed of three layers as shown in Figure 5: Crowd Simulation & Analysis. This layered architecture was initially introduced by Mahmood et al. and is now extended to focus on large scale buildings [4].

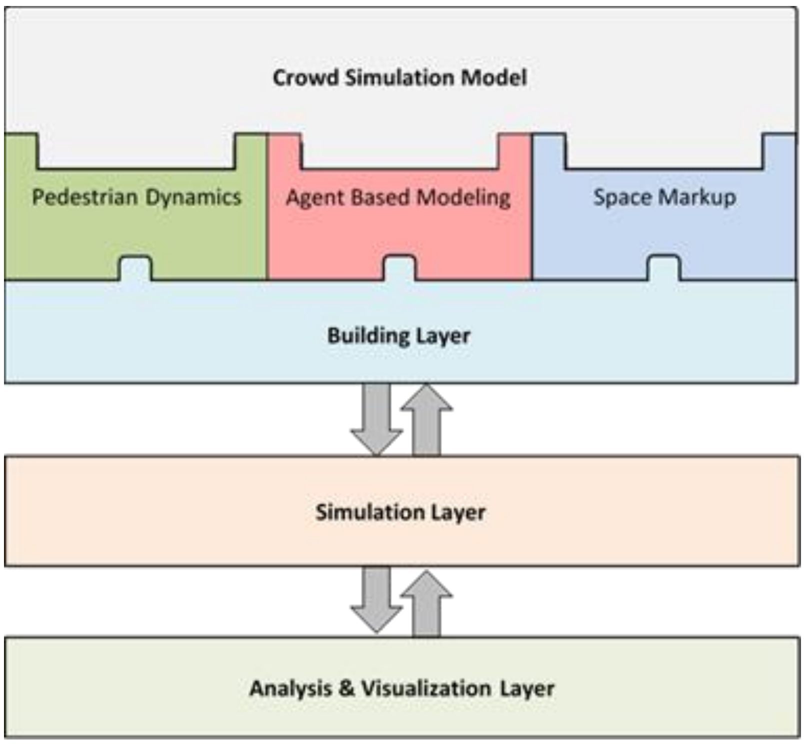


Figure 5: Crowd Simulation & Analysis

4.1.1 Building Layer

This layer comprises of three main components: (i) Spatial Environment, (ii) Agent Based Modeling and (iii) Pedestrian Dynamics. The main responsibility of the building layer is to ease the process of modeling complex building structures using CAD drawings and spatial markup tools, and to add walls, doors, passages, obstacles and the exit points in the building. It further allows the modeling of different pedestrian dynamics using agent-based approach, such as: Normal/Emergency walk speeds, normal/emergency pedestrian behavior, choice of exits during evacuation, arcing and clogging at exit points, avoiding obstacles, and choosing safe paths. The modeler can capture the physical environment of the building using CAD Drawings and can incorporate different features in the building using space markup tools, shown in Table 3.

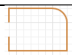
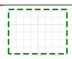
	**Wall**	Wall is used to define exterior and interior walls.
	**Target line**	Target line is used to graphically define the exit points in a building
	**Rectangular Area**	Rectangular area is used when your area is rectangular
	**Polygonal Area**	Polygonal area is used when your area has complex form.
	**Attractors**	Attractor allows controlling pedestrians positions and their movements inside an area.

Table 3: Space Markup Tools

The Space markup library within AnyLogic offers the necessary elements required for recreating a scaled graphical model of the spatial environment in which the agents will reside within the model [29]. Its different primitive elements such as, walls, polylines and pathways can help to make floor plans. Next, the modeler can create a logical flow of the pedestrians using the built-in Pedestrian library. The pedestrians are represented as agents with their physical and behavioral characteristics ranging from size (diameter of an average male or female), age, weight, height and gender, normal or handicapped etc. Based on the selected model resolution, the modeler may choose to incorporate these microscopic details in the model given that the tradeoff between the level of details and the execution performance is taken into account. In our proposed model, the pedestrian diameter is taken to be 0.5 meters, using a circular shape to express the approximate area covered by a single pedestrian. We assume the evacuation speed of the pedestrians to be 2.5m/s [30]. A real-scale floor plan of the actual building, developed using the building layer is shown in Figure 6: Floor Plan of a University Building.

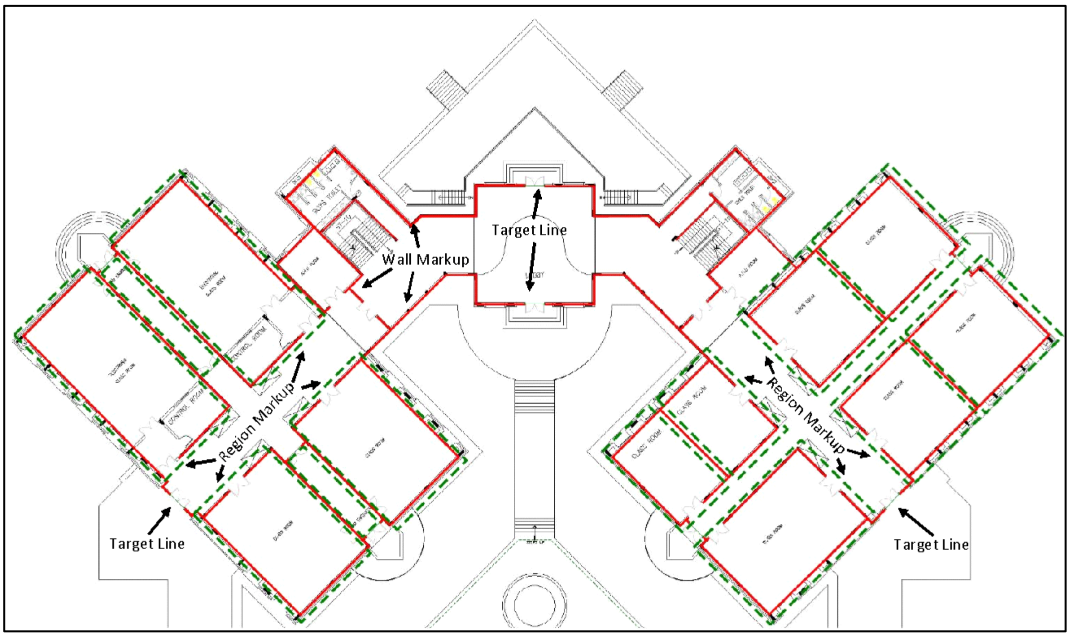


Figure 6: Floor Plan of a University Building

4.1.2 Simulation Layer

The simulation layer couples the building layer with the simulation environment. In this layer the modelers can create different simulation scenarios. It uses crowd simulation techniques to model the different patterns of a crowd and simulate it within the modeled building environment. It allows the modelers to control the flow of the crowd (or selected individuals) and direct the flows toward desired exit paths. It also allows to segregate the crowd into various sub groups and manage their evacuation. Figure 7: Ped Flow Diagram shows the basic pedestrian flow diagram developed in the simulation layer.

For the sake of simplicity and limited space we only present a single pedestrian source, which is injecting the agents into 5 regions where they wait indefinitely until this activity is cancelled by executing a 'Cancel-all' event, as shown in Figure 7: Ped

Flow Diagram. This causes all the pedestrians to start evacuating towards the five different exit points. The assignment of exits to each pedestrian (or the whole region) depends on the algorithm implemented in the "Exits" switch, which acts as a router and takes the decision of routing a pedestrian or a group of agents towards a suitable exit point. In this example a uniform probability is assigned for a random selection of any exit for all the pedestrians. Later we will discuss how intelligent algorithms can be implemented, that assess the overall situation and make effective decisions.

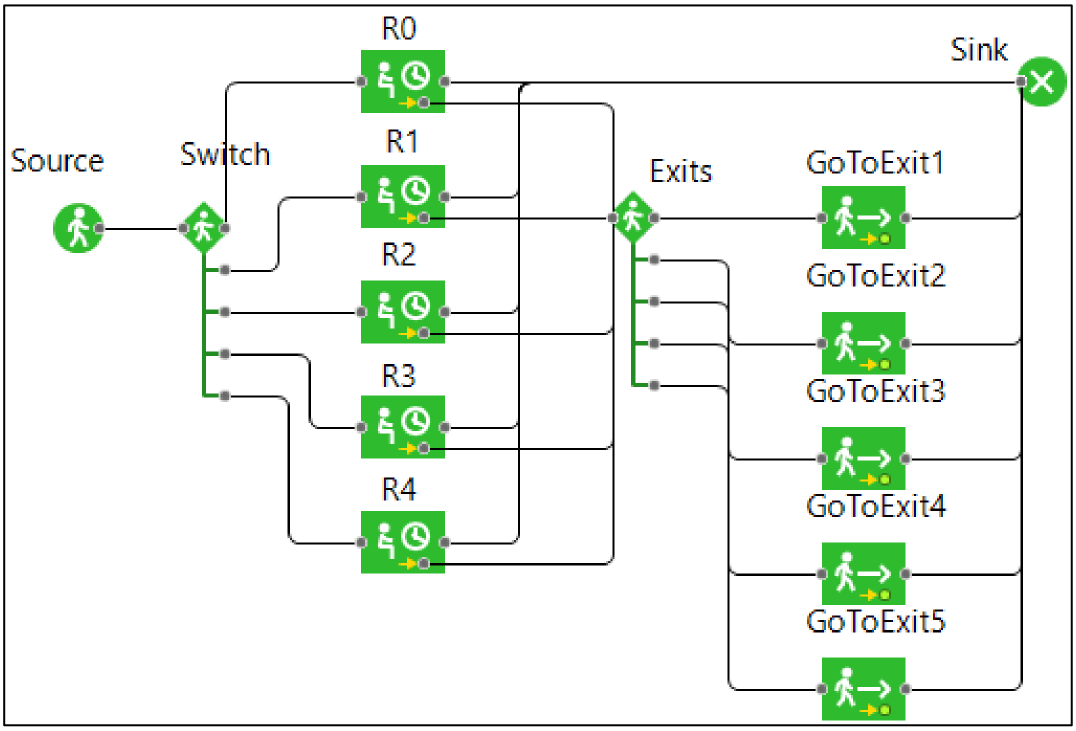


Figure 7: Ped Flow Diagram

In Figure 7, the block labelled 'Exits' directs the flow of the peds towards the various 'GoTo' blocks connected with it. AnyLogic allows the amount or flow of peds to be controlled through the 'Exits' block by assigning probabilities to the different outputs of the 'Exits' block. If the modeler wants the peds to be equally distributed amongst all the available exits, this can be achieved by simply assigning a similar probability to all the outputs as shown in Figure 8.

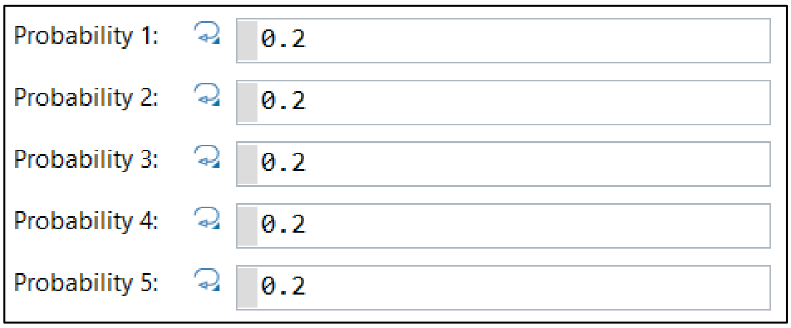


Figure 8: Assigning Probabilities in Switch

The various modelling blocks used to build the model in Figure 7: Ped Flow Diagram are illustrated in Table 4Table 4: Ped Flow Library.

	Source	Generates pedestrians
	Select	Routes the incoming pedestrians to one of the five output ports
	Wait	Causes pedestrians to wait for a specified time in a specified location
	Go to	Causes pedestrians to go to the specified target
	Sink	Disposes pedestrians

Table 4: Ped Flow Library

For further details, the readers are referred to the study conducted by Mahmood et al. [4].

4.1.3 Analysis and Visualization

This layer is used to implement and integrate different emergency evacuation strategies and their corresponding optimization algorithms. It further allows the analysis of different evacuation scenarios. This layer interacts with the simulation layer which further interoperates with the building simulation layer to run the model in a loop, using varied parameters, and retrieve back the results to be used as an input for the analysis layer. The analysis framework includes output analysis and visualization. Currently the graphical visualization of the evacuations includes time series and moving density charts. These charts are useful to analyze the outputs of different evacuation scenarios and their comparisons.

4.2 Proposed Emergency Evacuation Strategy and Algorithm

In this section, we present our proposed Emergency Evacuation Technique as an example to model the evacuation strategy, using our proposed algorithm called: Nearest Exit Shortest Time (NEST). NEST algorithm focuses on two primary goals. Firstly, the algorithm ensures that all the pedestrians inside the endangered building get access to the nearest exit and secondly, the pedestrians get divided amongst the available exits in such a manner that the chances of arching and clogging at the exits are minimized. This means that pedestrians are directed towards exits assigned to them by the algorithm based on their: (i) region in which they are placed; (ii) distances of these regions from all the possible exits of the building; and (iii) their time window within which they are supposed to evacuate, since not all regions can evacuate parallelly if the number of exits are limited, which otherwise will cause congestions at the exits. Therefore, the algorithm will compute a sequence of time windows for each region in order to organize the overall evacuation with minimal overall evacuation time. In our experience time sequence has proved to be better than simultaneous evacuations where congestion causes greater delays.

In order to explain the NEST algorithm, we constructed a simple spatial model consisting of 10 regions, all enclosed within a walled area having 7 exits randomly distributed on the boundary walls. The to-scale dimension of the boundary area is 120' x 120' whereas the dimensions of the inner areas range from 13' x 13'. Figure 9 shows the initial positions of the pedestrians whereas Figure 10 shows the exit assignments computed by the NEST algorithm. It can be seen that all the regions have been assigned T0 time window whereas R2, R6 and R10 are the three regions which are assigned to Exit1, Exit2 and Exit3 respectively and have T1 time window.

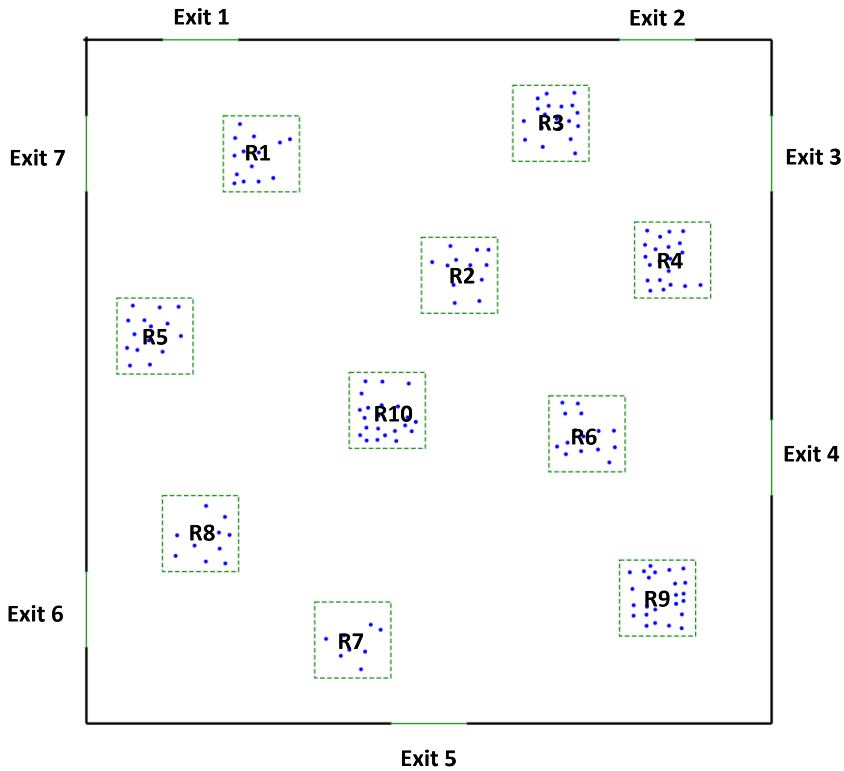


Figure 9: Emergency Evacuation using NEST Algorithm (initialization)

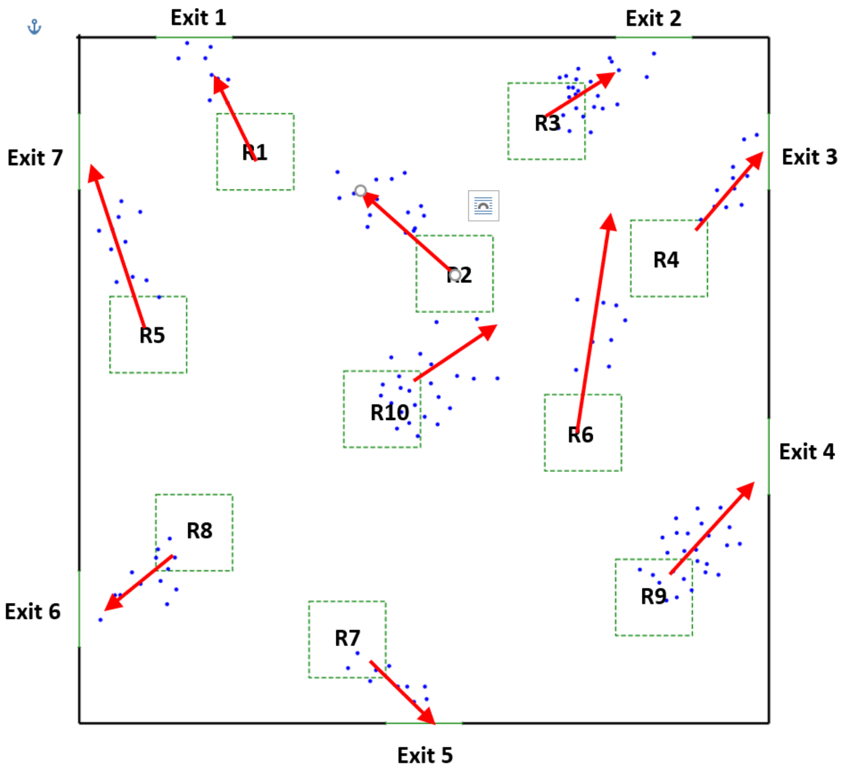


Figure 10: Emergency Evacuation using NEST Algorithm (evacuation)

Our proposed algorithm is presented in

.

Algorithm 1: NEST Algorithm

Input: Exits[m], Regions[n]

Output: Optimized Matrix

```
1  ▷ Initialization of Matrix
2  Matrix ←MxN
3  for each Exit i ϵ Exits do
4          for each Region ϵ Regions do
5              Calculate centroid distance of Region from Exit
6          end for
7  Sort distances in ascending order
8  Matrix [i] ← list of all regional distances from Exit i
9  end for
10
11             ▷ Optimization of Matrix
12             for each Exit j ϵ Exits
13                    Select the first occurrence of a region R
14                    Remove duplicates from matrix
15                    Perform shit left on the Matrix to fill the gap
16             End for
   ▷ Matrix optimized
```

Figure 11: NEST Algorithm

It takes a set of Regions defined in the building layer and the number of available Exits as input. In our above example we have 7 exits and 10 regions. It computes a matrix to output an optimized region-to-exit assignment solution based on different time windows. In line#2, the matrix is initialized. Line#3 - Line#9 initiates an iterative computation of matrix where the regions are placed against each exit in the ascending order of their distances. This sorting order can be replaced with other sorting rules e.g., descending order of priority, descending order of safety or shortest job first. Line#12 to Line#16 perform an iterative process of assigning the region to its most suitable exit and the time window. The details of these steps are illustrated in Figure 12.

Step 1:

	T0	T1	T2	T3	T4	T5	T6	T7	T8	T9
EXIT 1:	A1	A5	A2	A3	A10	A8	A4	A6	A7	A9
EXIT 2:	A3	A4	A2	A6	A1	A10	A9	A5	A8	A7
EXIT 3:	A4	A3	A2	A6	A9	A10	A1	A7	A5	A8
EXIT 4:	A9	A6	A4	A2	A10	A3	A7	A8	A1	A5
EXIT 5:	A7	A9	A8	A10	A6	A2	A5	A4	A1	A3
EXIT 6:	A8	A7	A5	A10	A1	A2	A6	A9	A4	A3
EXIT 7:	A1	A5	A2	A10	A8	A3	A7	A6	A4	A9

Step 2:

	T0	T1	T2	T3	T4	T5	T6	T7	T8	T9
EXIT 1:	A1	A5	A2	A3	A10	A8	A4	A6	A7	A9
EXIT 2:	A3	A4	A2	A6	~~A1~~	A10	A9	A5	A8	A7
EXIT 3:	A4	A3	A2	A6	A9	A10	~~A1~~	A7	A5	A8
EXIT 4:	A9	A6	A4	A2	A10	A3	A7	A8	~~A1~~	A5
EXIT 5:	A7	A9	A8	A10	A6	A2	A5	A4	~~A1~~	A3
EXIT 6:	A8	A7	A5	A10	~~A1~~	A2	A6	A9	A4	A3
EXIT 7:	~~A1~~	A5	A2	A10	A8	A3	A7	A6	A4	A9

Step 3:

	T0	T1	T2	T3	T4	T5	T6	T7	T8	T9
EXIT 1:	A1	A5	A2	A3	A10	A8	A4	A6	A7	A9
EXIT 2:	A3	A4	A2	A6	A10	A9	A5	A8	A7	←
EXIT 3:	A4	A3	A2	A6	A9	A10	A7	A5	A8	←
EXIT 4:	A9	A6	A4	A2	A10	A3	A7	A8	A5	←
EXIT 5:	A7	A9	A8	A10	A6	A2	A5	A4	A3	←
EXIT 6:	A8	A7	A5	A10	A2	A6	A9	A4	A3	←
EXIT 7:	A5	A2	A10	A8	A3	A7	A6	A4	A9	←

Figure 12: Steps 1,2 and 3 of NEST Algorithm

The final output of this algorithm is an optimized matrix which can be used by the Simulation layer to route the regions towards their assigned exits. The Final output of the algorithm divides the 10 regions into two time-windows, T0 and T1 as shown in Figure 12. The regions in the time window T1 will evacuate after the evacuation of the regions in tie window T0 (after a certain delay). This time window mechanism will help in preventing congestion at the exits during evacuation. The final output matrix shown in Figure 12 is applied in the evacuation of the scenario shown in Figure 10.

Chapter 5 Simulation and Results

This chapter demonstrates the functionality of our proposed framework. The proposed Algorithm is implemented in a case study and the results are discussed.

5.1 Case Study: Campus Evacuation

In this section we present the case study of the campus evacuation. After collecting the data from the university administration, we modeled a complete block of the campus building using building layer.

5.1.1 Building the Model Environment

In order to map the real-world environment into the simulation model, the to-scale image of the building environment is loaded into the AnyLogic program. This is done by going to the pallet section, then clicking on the presentation tab, clicking and dragging the image block onto the blank workspace. This will open up a pop-up window from where you will browse and select the image of the building you want to make the environment for as shown in

Figure 13.

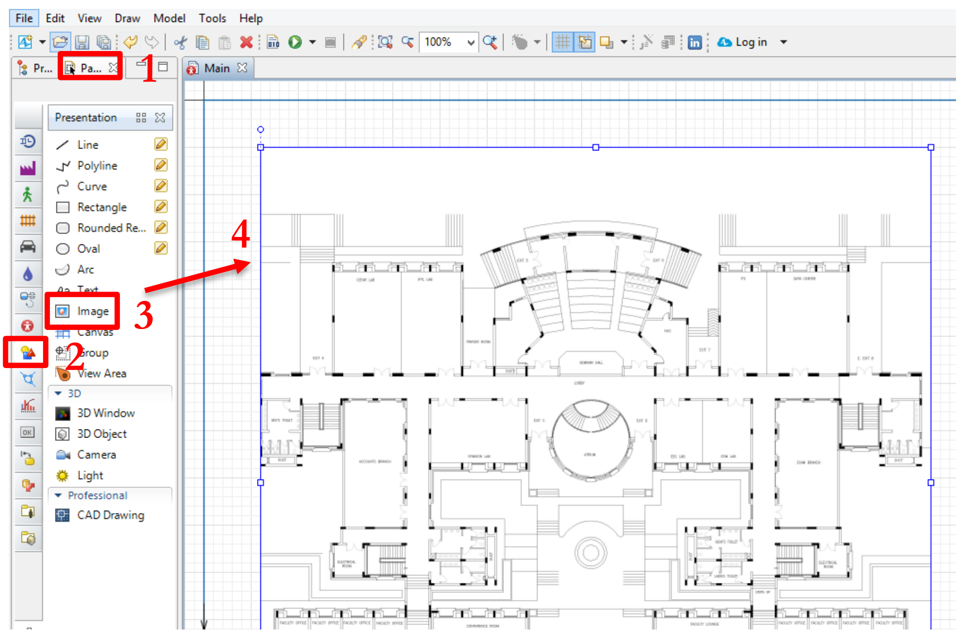


Figure 13: Importing the image into AnyLogic

Now the next step is to trace the walls onto the image we have just imported into the project workspace. In order to achieve this, in the palette section, go to the pedestrian library tab and double click on the wall icon as shown in Figure 14. This will enable the wall drawing mode.

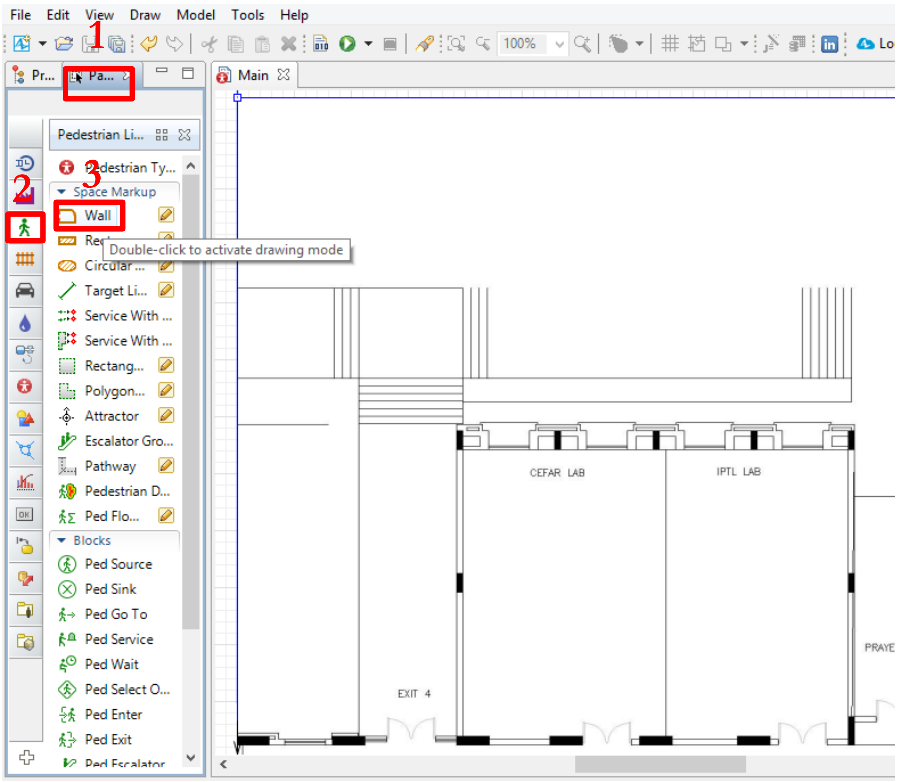


Figure 14: Selecting the Wall Markup Tool

Now go to your image and select a wall to trace. Click on the starting point of the wall and move the cursor over the straight path of wall and double click at the finishing point of the wall where you want to stop. Once you double click, the wall will appear with default settings. The properties tab on the right-hand side of the program will open automatically from where you can adjust the settings of the drawn wall as per requirements as shown in Figure 15.

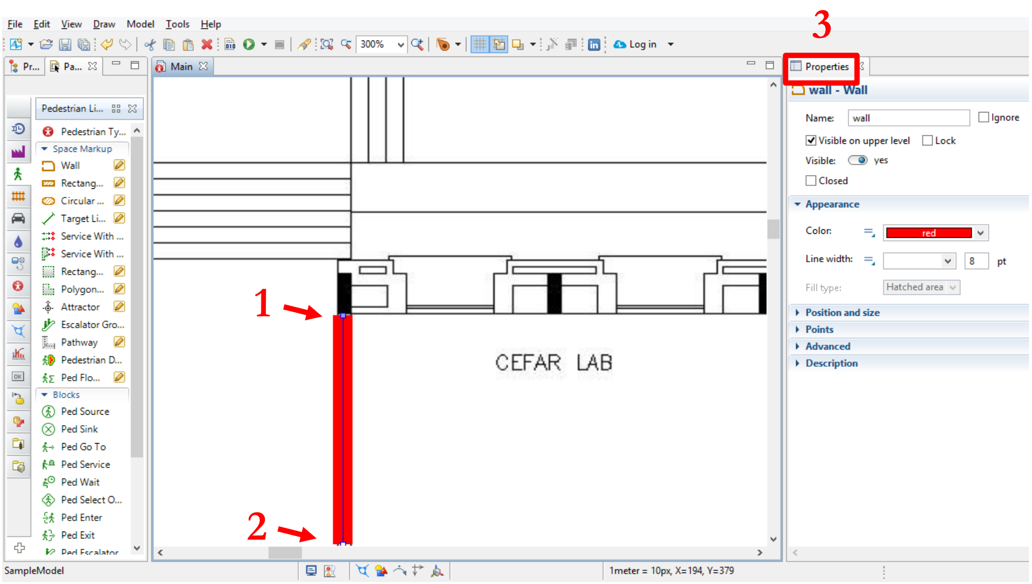


Figure 15: Tracing the Wall

After tracing all the walls onto the image, the *Areas* are also placed on the image in a similar manner. The end result will be similar to Figure 16.

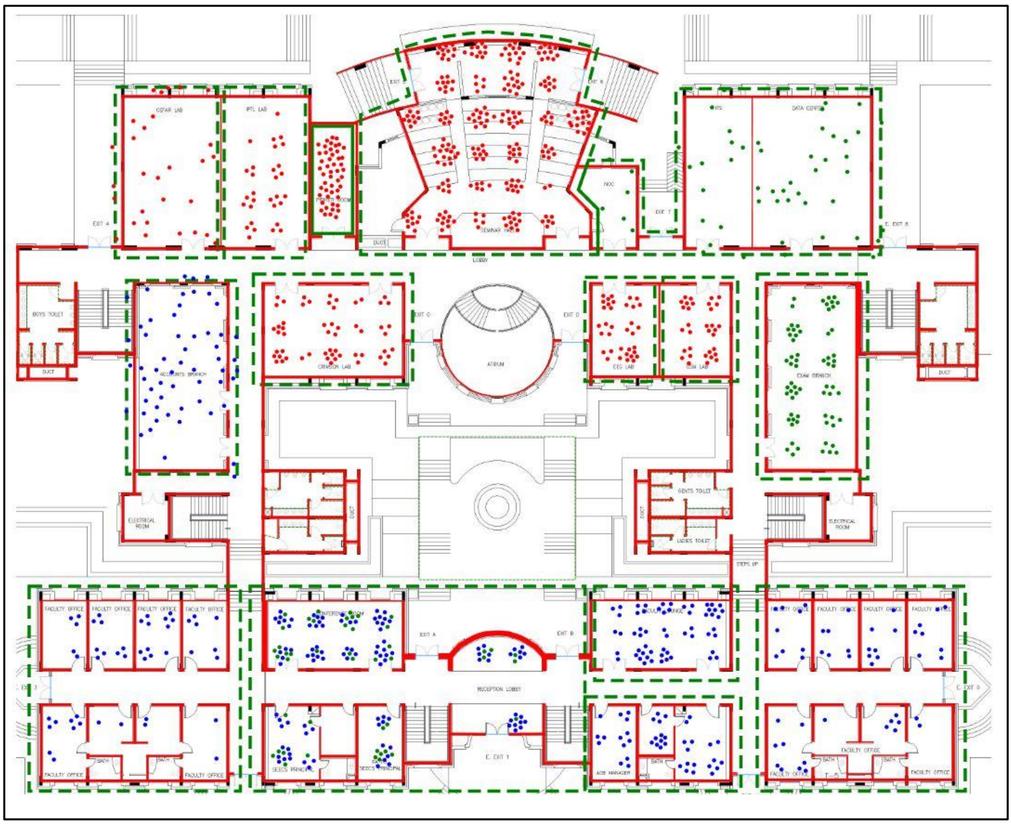


Figure 16: Ground floor of the Campus Building

The ground floor of the modeled building is shown in Figure 16. The ground floor of the campus building is divided into 15 regions and 10 Exits. The figure shows an initializing of three types of agents: (a) Red: Students, (b) Blue: Faculty and (c) Green: which depict working staff, guards and helpers respectively. The initial positions of each type of agent is as per the proportion of the real entities. The purpose of this distinction of agents is currently to initialize the population as per the collected data, however later it will be used to define the microscopic behavior of agents. E.g., the green colored staff is more trained in firefighting and rescue and can be modeled as leaders in the leader-follower protocol or can be engaged as first responders and first aid providers. In future the aim is to implement the microscopic behavior of different types of agents to address further complexities in the evacuation process.

5.2 Simulation

A pedestrian control flow using the simulation layer is developed. A total of three scenarios were run: (i) With 160 pedestrians, (ii) with 500 pedestrians and (iii) with 1000 pedestrians to evaluate the performance of our algorithm and its comparison with random evacuation. The Random evacuation is considered a worst-case scenario in any building evacuation because there is no evacuation plan and no predefined exit assignments. The pedestrians in random evaluation are randomly choosing their exits (based on uniform distribution) and may lead to longer paths and dense congestions. Also due to the continuous interruptions of motions, in order to avoid collisions, there will be additional delays. We choose this scenario as a lower bound to compare our developed algorithm with. In Figure 17, Figure 18, Figure 19 and Figure 20 we can see the different stages of the simulation being run. The total time taken for the evacuation of 200 agents using NEST algorithm took a total of 1 minute and 5 seconds as shown in Figure 20.

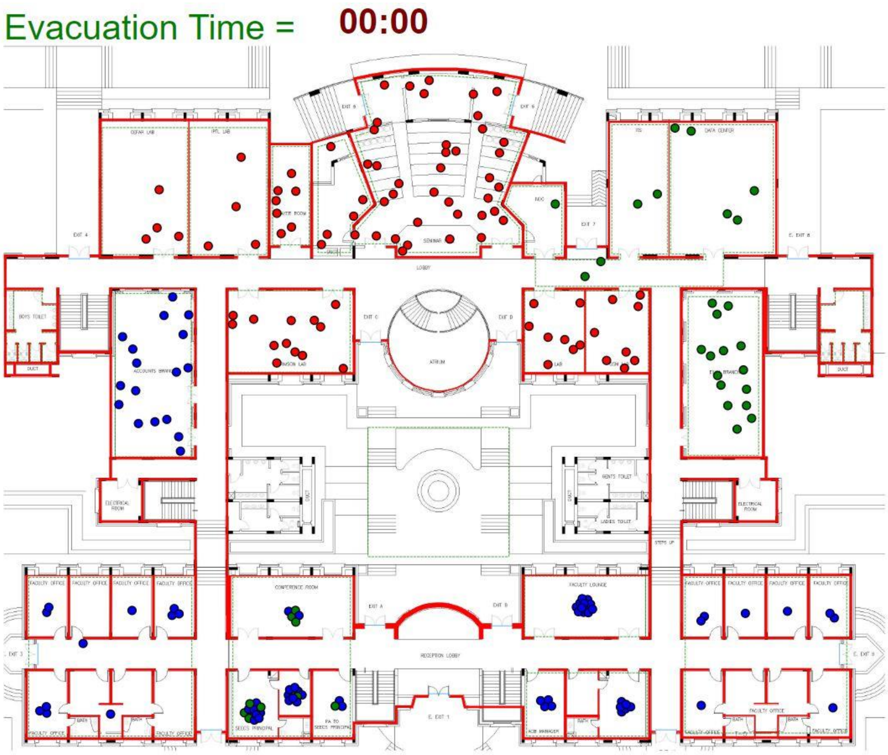


Figure 17: Emergency Evacuation of Building at time 00:00

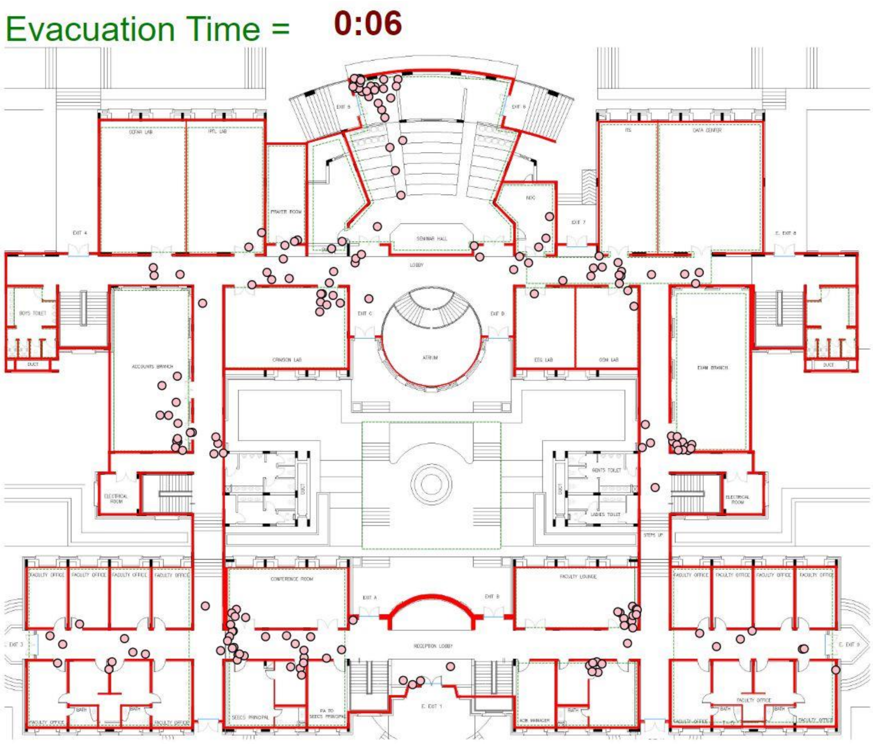


Figure 18: Emergency Evacuation of Building at time 00:06

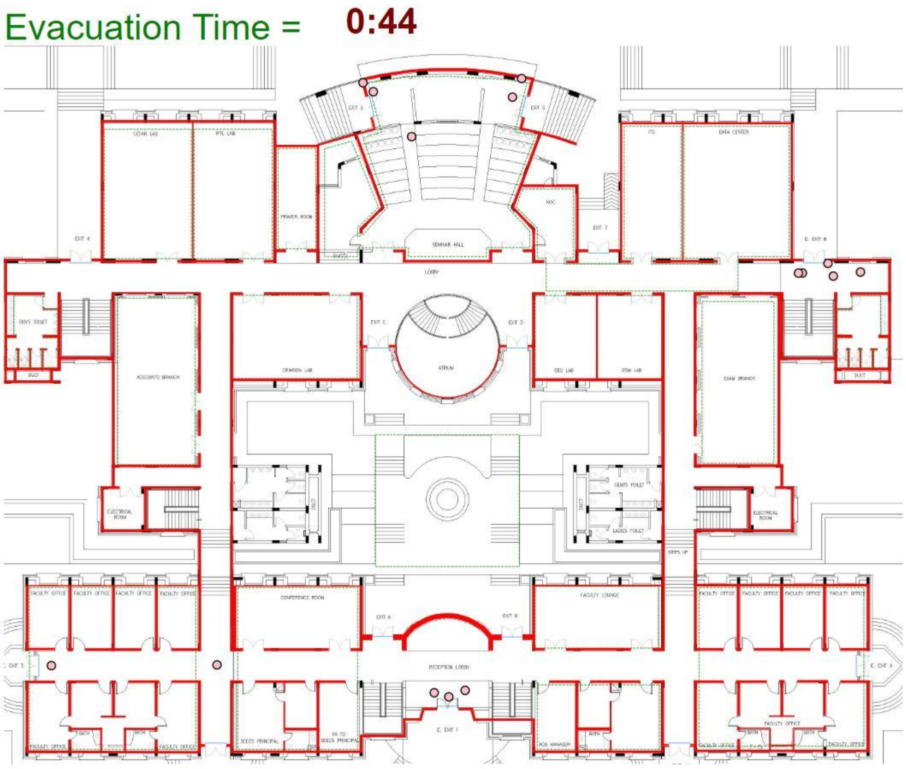


Figure 19: Emergency Evacuation of Building at time 00:44

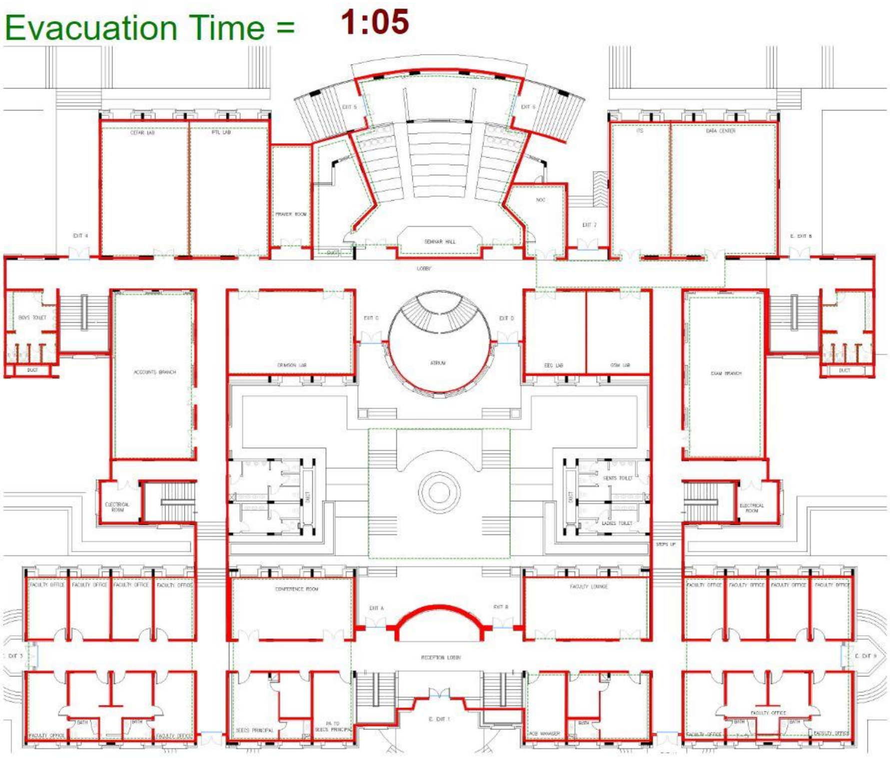


Figure 20: Emergency Evacuation of Building at time 01:05

5.3 Results

Figure 21 shows the results of the simulation scenario with 160 peds. Figure 22 shows the results of the scenario with 500 peds and Figure 23 shows the results of the scenario with 1000 peds.

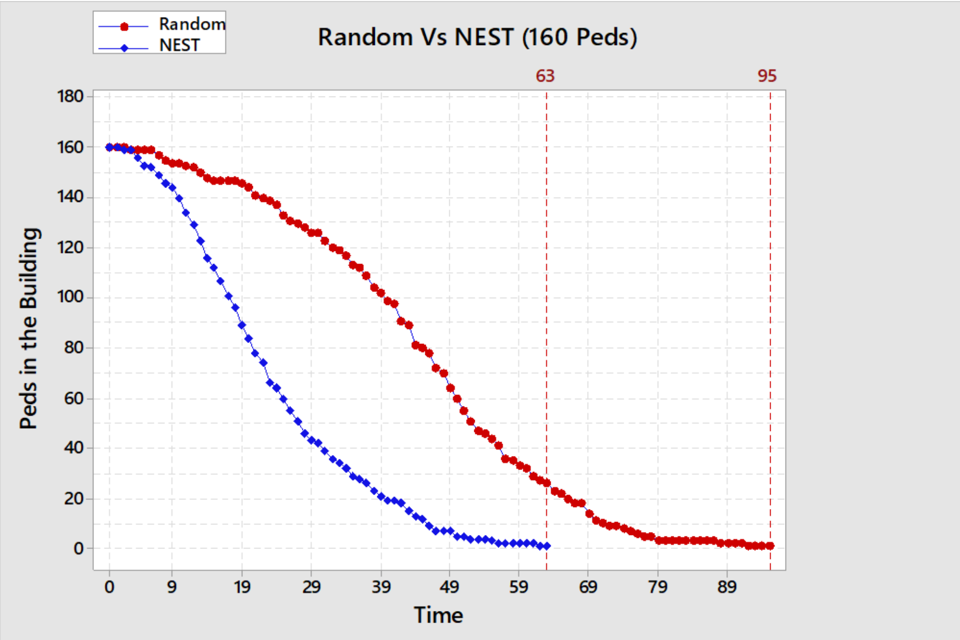


Figure 21: Simulation Scenario 160 Peds (Time in Secs)

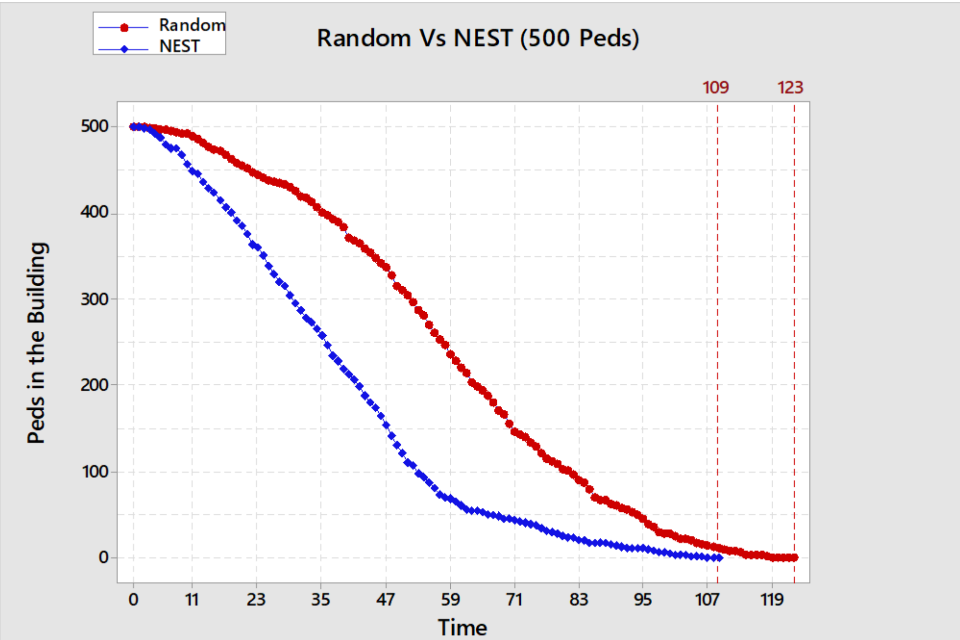


Figure 22: Simulation Scenario 500 Peds (Time in Secs)

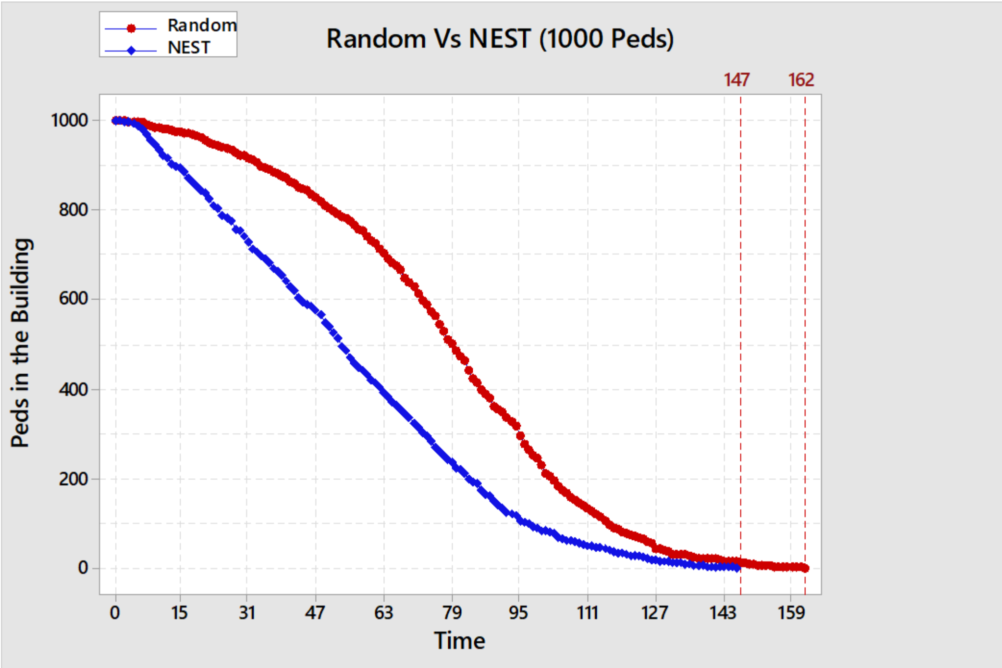


Figure 23: Simulation Scenario 1000 Peds (Time in Secs)

It can be seen from the results that the NEST algorithm performs better than the random evacuation. It can however be observed that if the population is scaled up even NEST algorithm finds it harder to avoid congestion i.e., the slower descent near the finishing time. We used the AnyLogic University Researcher Edition 8.2.4, (AnyLogic 2019) for the development and the execution of the Crowd Simulation and Analysis framework. The hardware and OS specifications are: DELL OptiPlex 3046 Intel(R) Core (TM) i7-6700 CPU @ 3.40 GHz, RAM: 8GB, Windows 10 Education. The execution times for the NEST algorithm for each scenario are: 63 sec, 109 sec and 146 sec. Whereas the execution times for the Random algorithm for each scenario are: 95 sec, 123 sec and 162 sec respectively.

5.4 Model Validation

The accuracy of the AnyLogic simulator was validated by conducting real-world experiments and comparing the results of the simulated experiments using the same parameters as of the real-world environments. We picked each region (enclosed in red) as shown in Figure 27 and calculated the time taken to reach the predefined exit (highlighted in blue) by doing multiple on ground runs from the predefined set of regions to the exits (sample path shown in Figure 26). Simultaneously, we used a pedometer mobile app shown in Figure 24 to monitor the time taken and also to monitor the pedestrian speed during the runs.

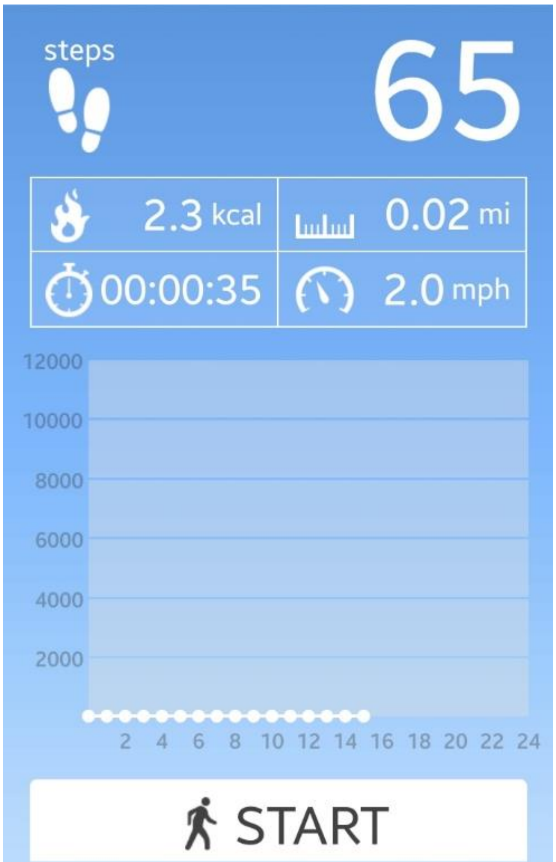


Figure 24: Screenshot of Pedometer Mobile Application

We can see in the above screenshot of the pedometer application that it provided us with all the essential information that we needed. The essential features for us were the pedestrian walking speed, the distance covered and the tie taken for the complete run. These features were saved for each run conducted in the mentioned building. The saved pedestrian speeds for each path were entered into the simulator for the corresponding path in order to maintain the accuracy of the results. The obtained results of both the real and simulated runs for each path are shown in Figure 27. The ties of both the actual and simulated runs were compared to analyze the validity and accuracy of the simulation framework being used

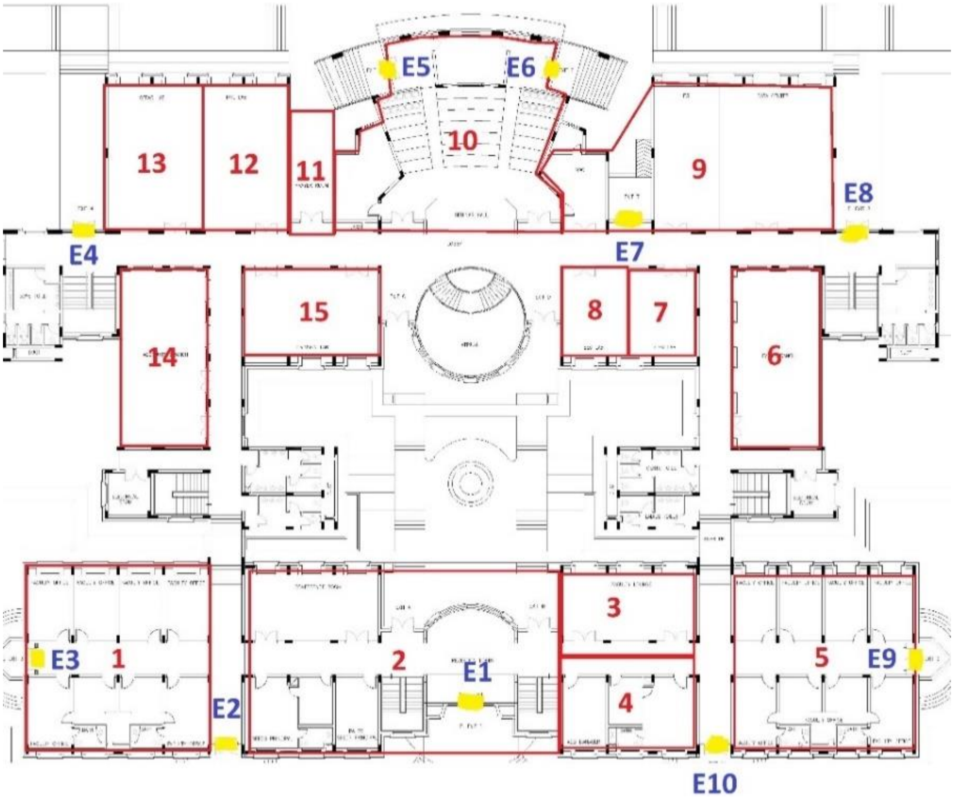


Figure 25: Division of The Regions for Validation

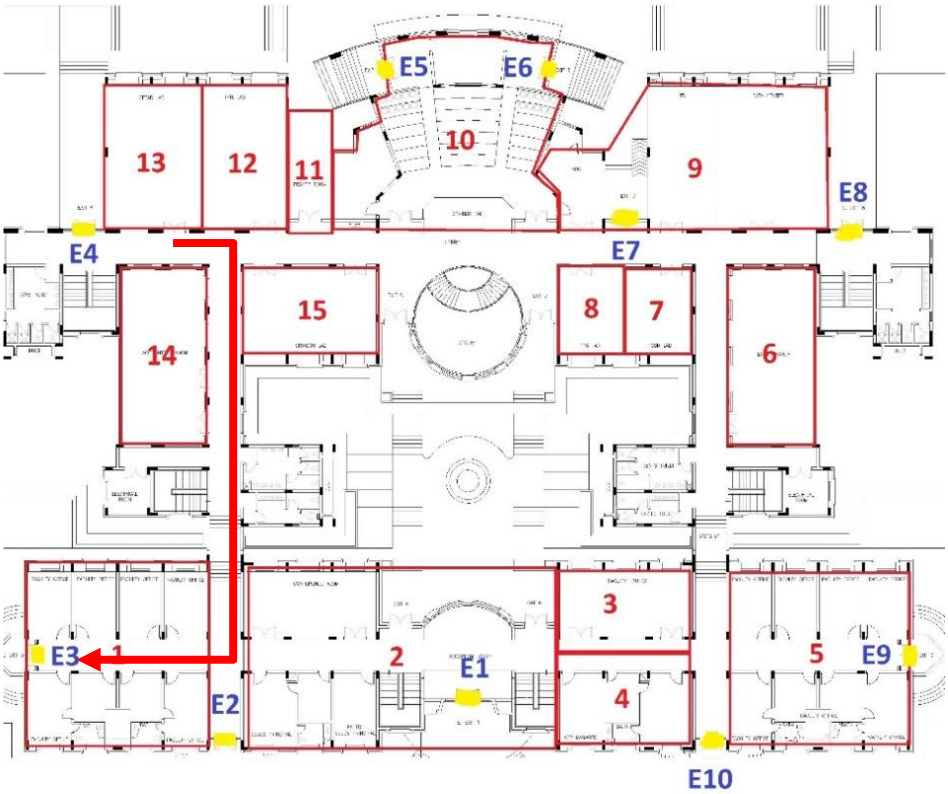


Figure 26: A Sample Path From Region 13 to Exit 3

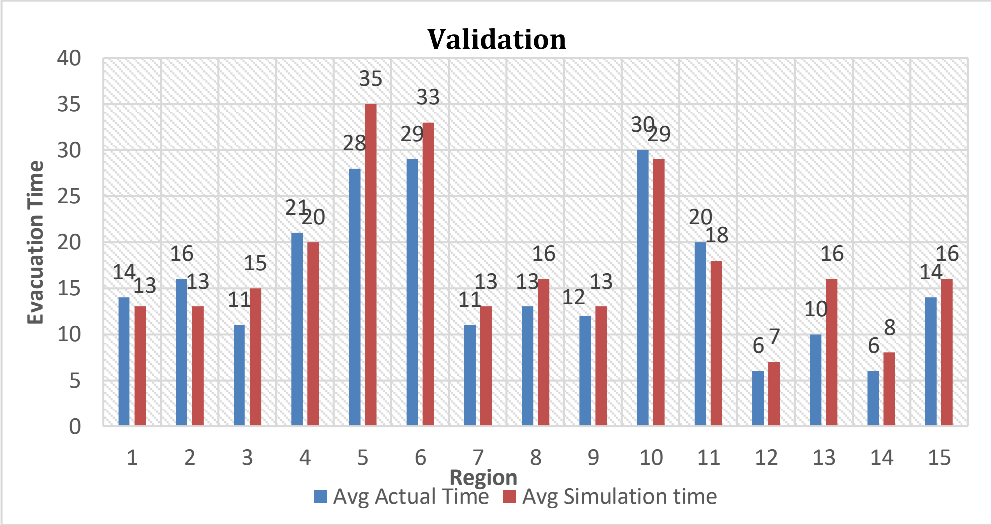


Figure 27: (a) Validation Results (b) Pedometer Mobile App (Time in Secs)

5.5 Approach Validation

The Table 5 below present the comparison between the various crowd simulation frameworks that have been used to study the dynamics of crowd movements [11]. The horizon column describes whether the model under consideration is a long-term crowd process or a short-term crowd process. Long-term processes are those which take time to evolve through a population of individuals such as the evolution of ideologies amongst a region. Short-term processes are those which occur within minutes or hours such as evacuations or pedestrian traffic through a region. The crowd scale defines the population of the crowd. Large referring to hundreds of thousands of individuals, medium referring to thousands of individuals and accordingly, small referring to hundreds of individuals. Application area defines the area aimed to be studied using the model. Resolution defines the level of details incorporated in the model. Micro level refers to the inclusion of the cognitive behavior of the agents being modelled along with their decision-making abilities and as well as their ability to weigh decisions based on a number of factors. Extensibility refers to the ability of the model to be extended to other domains. Scalability refers to the ability of scaling the model to a larger or smaller scale of deployment.

Model Name	Horizon	Scale	Application Area	Model Goal	Type of Approach	Resolution	Social Network	Decision Theory	Extensibility	Scalability
Deffuant	Long Term Crowd Process	Large	Social Study	Formation/spread of Ideologies Amongst Crowds.	Entity Based	Micro	Yes	Yes	No	Yes
Salzarulo				Formation/spread of Ideologies Amongst Crowds.	Entity Based	Micro	Yes	Yes	No	Yes
Evacnet4	Short Term Crowd Process		Civil Planning	Impact of various environmental factors on the movement of the crowd.	Flow Based	Meso	No	No	No	No
Flow Tiles			Digital Entertainment	Impact of various environmental factors on the movement of the crowd.	Flow Based	Meso	No	No	No	Yes
Continoum Crowds		Medium	Digital Entertainment	Impact of various environmental factors on the movement of the crowd.	Entity Based	Meso	No	No	No	No
VRLab@EPFL				Focuses on the path planning for the crowd.	Entity Based	Meso	Yes	No	No	Yes
MRL@NYU				Developing a comprehensive behavior model for animating virtual pedestrians.	Agent-Based	Meso	Yes	Yes	No	Yes
Helbing			Operational Study	Physics and socio-psychological forces.	Entity Based	Meso	No	Yes	Yes	No
ITP@UC				Simulate pedestrian traffic using the particle system approach.	Entity Based	Meso	No	Yes	Yes	No
CASA@UCL			Civil planning	Modelling and simulation of the dynamics of pedestrian movements in spatial events.	Entity Based	Meso	Yes	Yes	No	No
Legion@Crowd Dynamics				Global path planning algorithm for agents.	Agent-Based	Macro	No	No	Yes	No
VMASC		Small	Military Training	Psychologically-based real-time interactive crowd model for military simulation.	Agent-Based	Meso	No	Yes (Crowd Level)	No	No
CHMS@UPenn				Improving the realism of human behavior models by integrating a set of psychological factors.	Agent-Based	Macro	No	Yes	No	No
Proposed Framework	Short and Long Term	Large	Any	Focuses on the shortest path planning coupled with decongestion for the crowd combined with the impact of environmental factors.	Agent-Based Path Planning	Micro	Yes	Yes	Yes	Yes

Table 5: Comparison between crowd simulation frameworks

Based on the table, we can see that the AnyLogic simulation framework chosen by us for the development and simulation of the proposed algorithm supports combined features that are offered separately to other simulation frameworks. Its scalability and extensibility enable it to be used for large scale and wide range of application areas. AnyLogic can handle large scale simulations which allow it to run hundreds of thousands of agents given the required computing power. The micro resolution offered by the framework enables the modelers to define the behavior and reactions (social, economical, personal, etc.) of individual agents. This feature extends to social network and decision theory as well. The readily available pedestrian library allows the modeler to focus more on the semantics of the model. The java enabled platform allows for more detailed and complex implementations of models.

5.6 Algorithm Performance Comparison

In this section, a comparison is made between available datasets of building evacuations conducted and the proposed NEST algorithm [31]. The available evacuation datasets were either planned drills or were actual evacuations. Not all of them have the walking speeds available for the pedestrians during the time of the evacuations due to some constraints. One thing to keep in view is that NEST algorithm has only been implemented on a single-story building and also assuming that there are no physical obstacles in the rooms other than the walled structures of the building (due to the level of abstraction). The comparison is shown in **Error! Reference source not found.**.

Evacuation Venue	Evacuation Type	Exits	People Evacuated	Time Taken (secs)	Walking Speed (m/s)	Person /Sec
Highschool Building (Multistoried)	Drill	5	596	425	1.4	1.40
Highschool Building (Multistoried)	Drill	3	148	366	0.85	0.40

Supermarket Inside a Shopping Centre	Real	4	231	450	n/a	0.51
A Shopping Center (Multistoried)	Drill	4	100	240	n/a	0.41
Comprehensive School (Multistoried)	Real	3	245	225	n/a	1.08
Primary School (Multistoried)	Drill	3	201	89	n/a	2.25
SEECS Ground Floor	**Simulation**	**10**	**200**	**64**	**1.5**	**3.12**

Table 6: Comparasion With Other Evacuations.

The last column, 'Person/Sec' is a measurement index introduced in the table to help in an easier analysis between the people to time ratio taken for all the mentioned evacuations. This index shows us the number of people evacuating per second. The performance of NEST algorithm is mentioned in the last row of the table for comparison purposes. We can see that the person/sec index is highest for the NEST algorithm, meaning that the person per second ratio is highest for the NEST algorithm.

Chapter 6 Conclusion and Future Work

This chapter provides the Summary, conclusion and future work of the thesis.

6.1 Summary

In this research, a Crowd Simulation and Analysis framework is proposed for the emergency evacuation modeling, simulation, visualization, analysis and the optimization of large buildings, using real-scale building structures and agent-based approach. Furthermore, an algorithm is proposed called: Nearest Exit Shortest Time (NEST), in order to devise an evacuation strategy, that not only assigns exits to different regions based on shortest distances but also load balances the crowd at the different exits by using different time windows. The functionality of our algorithm is demonstrated using a simplistic example and apply the algorithm in a campus evacuation case study using three scenarios. The algorithm outperforms random evacuation and scales up when the population is increased. The focus of this research is to propose an evacuation strategy using NEST algorithm and apply it in a real world setting to demonstrate effective building evacuation using crowd simulation framework.

6.2 Conclusion

The simulation framework will help develop strategies/policies for effective emergency evacuation plans. It can also be used to analyze existing plans and identify their performance. The proposed algorithm can further be extended for complex scenarios where priority evacuation is needed, or the exits are to be selected based on safe pathways, in order to avoid paths with fire or blocks. In case of insurgency strikes, the dynamic shift of exit assignments will also be possible.

6.3 Future Work

A mobile app will be developed to collect real-time data of pedestrian trajectories which can be used to calibrate real evacuation drills with the simulated evacuation for further validation and assessment. Also, existing evacuation strategies can be implemented in our framework from the scratch and their performance compared with our proposed algorithm in future. Color schemes can be projected on the floors of the pathways using colored projectors, to guide the pedestrians to follow the paths based on their assigned colors. The framework can be extended to support complex scenarios including fire, earth quakes and insurgency strikes, which require special training, counter measures and effective response management.

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