THE UNIVERSITY OF SHEFFIELD

Doctoral Thesis

Crowd Modelling and Simulation

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A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

in the

Department of Computer Science

Apr 2017

THE UNIVERSITY OF SHEFFIELD

Abstract

Faculty of Engineering
Department of Computer Science

Doctor of Philosophy

Crowd Modelling and Simulation

by Omar Kurdi

In this thesis we analysed the behaviour of crowd flows in large gatherings, taking a case study of the corridors where the *Sa'yee* ritual are performed. Of the current simulation models few of them addressed disabled persons in their model calculations and they did not include real-life data in order to analyse the crowd behaviour. None of the crowd modelling and simulation studies of the Hajj crowd, focused mainly on crowd behaviours during the *Sa'yee* ritual.

We have proposed and developed a methodology to extract crowd characteristics from real-life videos with unknown camera angle and position. Agent tracking for different conditions of weather and various walking styles have been studied in the scope of our study. We further tested the feasibility of the use of drone to track agent behaviour in our methodology. We propose, design, and develop, a realistic and flexible state-based model of the *Sa'yee* ritual that can be mapped onto different agent-based systems, and then implement it in the modelling platforms Netlogo and FLAME. Further a comparison is made in terms of processing speed so that the model could be escalated to larger crowd. There are two enhancements carried out in the *Sa'yee* model and simulations, that makes this research novel and different than other contemporary researches. The first is the addition of different types of people (men, women and people with disabilities) , and the second is the use of real video recordings from CCTV to analyse and model the walking behaviours of pilgrims. We carried out experiments that define the safety limit for the number of people in a group, and the results of defining a dedicated corridor for the disabled population. An empirical study shows that some aspects of the model such as agent density, behaviour, and speed match the real *Sa'yee* crowd. Therefore, the model can be used to study the general crowd behaviour in terms of agent density and speed of the agents with only slight modifications.

The model is mapped from Netlogo to FLAME which validates that our model can be extrapolated to simulate larger crowd and huge number of agents. In addition, safety guidelines for better crowd management have been proposed to enhance crowd flow and reduce risks.

Acknowledgements

First of all, I am most thankful to almighty Allah (God) for giving me the strength and providing me with blessings to accomplish this work. I would like to express my deepest gratitude to Dr. Mike Stannett, thank you for helping to guide and outline the direction of this thesis with your careful and instructive valuable comments, from the beginning till the end. I would also like to thank Prof. Marian Gheorghe (my previous supervisor), who provided his support during the first three years in my PhD project. I am grateful for his insightful suggestions and discussions, and for all his input into this project. It is a pleasure to acknowledge those who made this project possible, such as Prof. Daniella Romano, for her encouragement to actively play a part in her group and to publish data from my work, Dr.Mariam Kiran and Dr.Ilias Sakellariou who have had an important academic influence on me, their advices has been always enormously helpful There is no way to express how much it has meant to me to be a student at the University of Sheffield. I have been surrounded by wonderful staff and colleagues, and brilliant friends in the VT lab, all of whom have provided a productive and rich atmosphere to study and explore new ideas. I take this opportunity to sincerely acknowledge the Ministry of Higher Education in the Kingdom of Saudi Arabia for awarding me the PhD degree scholarship. My research project would not have been possible without their outstanding help and financial support throughout this scholarship. I am most grateful to my parents: mum, Farida Kamel, the source of unconditional constant love, and especially to my father, Dr.Abdullatif Kurdi that had passed away when I was a kid. I do not really remember my father a lot, but I know that he always stressed the importance of learning, and this respect for education has made me the person I am today. Words are truly short to express my deep sense of appreciation towards my parents. I have been also blessed with a very supportive and loving brothers and sisters, all of whom have always encouraged me with their prayers and best wishes. Being a father, without any doubts, has been the source of inspiration and my highest achievement. Fatherhood has taught me how to provide unconditional love and how to be a better person. To my greatest blessings, my kids, Faisal, Talal, Rama and Faris, your little cheerful smiles brightened my life. You have helped me to get through this tough period and presented incredible patience in the most positive way during my long working hours for the past four years. I am grateful to have you and to raise you. There are no words to express how much I love you all. Last, but never least, I owe a sincere thank you, with love, to my amazingly supportive soul mate, my wife, Manar Samman. You are my enthusiastic continuous supporter, always cheering me on, my best friend, and the wonderful wife and mother I always dreamt of. You shared this marvellous journey with me, and we have been through good and hard times together; hence, it seems only right that I dedicate this thesis to you. I will be endlessly grateful to you.

Declaration of Authorship

The work presented here is my original work and it is undertaken during my PhD course at the University of Sheffield from December 2011 to December 2015. Some of this work has been published separately in:

- Sakellariou, I., Kurdi, O., Gheorghe, M., Romano, D., Kefalas, P., Ipate, F. and Niculescu, I. (2014) *'Crowd formal modelling and simulation: The Sa'yee ritual'. In Computational Intelligence (UKCI), 14th UK Workshop on (pp. 1-8). IEEE.*
- *Kurdi, O., Stannett, M.and Romano, D. M. (2015) 'Modelling And Simulation Of Tawaf AND Sa'yee: A Survey Of Recent Work in the Field'. ESM'2015, Leicester, UK*

Signed: ____

Date: ____

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Abbreviations

AAS	**A**verage **A**gent **S**peed
ABM	**A**gent **B**ased **M**odelling
ABMS	**A**gent-**B**ased **M**odeling and **S**imulation
AS	**A**gent **S**peed
CA	**C**ellular **A**utomata
CSAI	**C**omplex **S**ystems and **A**rtificial **I**ntelligence
CTHMIHR	**C**ustodian of the **T**wo **H**oly **M**osques **I**nstitute of the **H**ajj **R**esearch
DES	**D**iscrete **E**vent **S**imulation
DT	**D**istance **T**ravelled
DSL	**D**omain **S**pecific **L**anguage
FLAME	**F**lexible **L**arge-scale **A**gent **M**odelling **E**nvironment
FLAME GPU	**F**lexible **L**arge-scale **A**gent **M**odelling **E**nvironment **G**raphics **P**rocessing **U**nit
FPS	**F**rames **P**er **S**econd
GDT	**G**ranulometric **D**istribution **T**ool
GIS	**G**eographic **I**nformation **S**ystems
GPS	**G**lobal **P**ositioning **S**ystems
GPU	**G**raphics **P**rocessing **U**nit
GUI	**G**raphical **U**ser **I**nterface
MAS	**M**ulti-**A**gent **S**imulation
MASON	**M**ulti-**A**gent **S**imulator **O**f **N**eighbourhoods
NF	**N**umber of total **F**rames
RVO	**R**eciprocal **V**elocity **O**bstacles
REPAST	**RE**cursive **P**orous **A**gent **S**imulation **T**oolkit
RSM	**R**esponse **S**urface **M**ethodology
SIM	**S**ubscriber **I**dentity **M**odule
TD	**T**ime to travel the **D**istance

XXML	**X**-machine e**X**tensible **M**ark-up **L**anguage
XSLT	e**X**tensible **S**ty**L**esheet **T**ransformation

Chapter 1

Introduction

1.1 Introduction

Modelling and simulation are concerned with getting information pertaining to the behaviour of a system, without actually testing it in the real-life. It plays a very important role in research, and allows the exploration of system behaviour in a way that is often either not possible or too risky in real-life. Simulation and modelling can save valuable time and resources. In some cases, it is not feasible to recreate the real life situations concerning the possibility of some risks, such as those with a large size and so on. For our case study of crowd behaviour, it is difficult for us to study its behaviours in real time; hence, such a significant and heterogeneous study can be properly realised using a robust simulation environment. Crowds occur everywhere, from schools to shopping malls and from universities to holy places. As such, we chose a study of crowd behaviour that can be generalised to crowds occurring at any place at any time. The simulations have to be correct, and only we can ensure proper results at the end of each modelling. In this research, we validate accuracy through the use of various validation techniques demonstrated in [4], as we have calibrated the model parameters, such as walking speed and density. The simulation involves various agents in the form of individual members of the crowd. An agent literally means doer of an action or an activity [5]. For our modelling case, agents specifically represent any individual member simulated in our software and who is involved in the collective action of Hajj. We can define an agent as an autonomous, goal-oriented and collaborative subject that can take its own initiatives, exercise a non- trivial degree of control of its actions, accept requests as an intellectual human being, and understands how the request is satisfied. Further, it should be able to manipulate requests and seek clarification for the requests to be verified and, in some cases, denied so as to follow certain requests. Agent-based modelling (ABM) is the manipulative study of autonomous agents, indicating all their possible interactions, and their outcomes. It is a study tool that simulates and models the behaviours of a huge and heterogeneous system, which, otherwise, would be too risky and infeasible in real life scenarios [6].

Many scientific modelling applications use equation-based modelling, which uses proven mathematical expressions in the form of simulation. Such equation-based modelling is useful in terms of recreating and consistently obtaining similar results relating to the study of the problems of concern; however, in order to model something, such as a collective action or a strategic co-ordination (like crowd behaviours), there comes a modelling need where we can represent the entities as multiple autonomous agents. ABM seems just right in terms of simulating and modelling complex systems unbound to fixed restrictions with dynamic behaviours and rules.

Understanding of this complex issue can be garnered on the basis of previous studies and case study researches, which allow us to explore all details and which will help us to anticipate the final output[7].

1.2 Aim and Scope

The aims of this thesis are as follows :

1. Developing a piratical method of extracting data, parameters and patterns of people walking behaviours in the crowded events from video recordings;
2. Design a reliable and customisable simulation model to any similar facility (corridor);
3. Build a simulation model based on real data and capable of producing consistence results;
4. Implement the designed model on ABM platforms that are support simulation of large scale crowd events such as *Sa'yee*.

The model should be aid to reduce the number of potential incidents that may occur during crowd movement and hence provide a safer environment, specifically in public places (stadiums, shopping centres and holy places, etc.) where high congestion can occur.

In order to achieve the above aims, the model is required to be:

1. *Quick*: producing measurements in an acceptable time frame i.e. hours, or at most a few days. These measurements depend on certain factors, such as the number of agents in the model, the runtime of simulations, and computer performance, etc.
2. *Accurate*: to increase the accuracy of the model results through the use of real data extracted from real-life case.
3. *Flexible*: can be applicable to different cases, locations, speeds, behaviours, number of agents and group sizes with a limited amount of modification during the simulation process.
4. *General*: should include a diverse crowd population, including varying ages of men, women, disabilities, individuals, and groups with adjustable sizes.
5. *Trusted*: should produce consistent and predictable results that can be verified and validated.

In order to satisfy the above requirements, we have executed the following work:

1. Collected real-life videos from six different locations (shopping malls, open market, Universities, and holy places) to observe walking behaviours of people in different areas and conditions.
2. Developed a technique to extract crowd characteristics from videos taken by unknown camera type and settings.
3. Verified the proposed speed extraction technique.
4. Choose one of the largest crowded areas in the world as a case study, i.e. (religious yearly ritual in Saudi Arabia) the performance of Hajj at Al-Masjid Al-Haram, to develop a working model that satisfied the above requirements.

5. Reviewed and compared the recent research in the field of crowd modelling and simulation, especially those pertaining to providing solutions for efficient crowd management and organisation during the Hajj rituals.

6. Analysed and studied various commonly used agent-based modelling platforms that meet the proposed model's requirements.

7. Proposed and investigated techniques centred on simulating crowd member behaviours.

8. Devised validation methods to verify the results of the proposed simulation model.

The scope of this thesis is focused on building a method for extracting crowd flow characteristics from real time videos, before using them to feed the chosen case study. And finally, modelling and implementing a simulation model for the case study. Further, analysis and validation of the results to ensure the accuracy and capability of our simulation, and finally suggest a better crowd management solution to provide safer flow for the people with disabilities.

One of the important issues whilst building any public facility, such as a shopping complex, is to determine the optimal location for exits and the reasonable wide of corridors, etc. This shows the need to identify further extensive and accurate ways so that they reflect thorough flow plans about general facilities. Potential problems can be identified in advance through appropriate simulation, and can be further generalised so that crowd behaviours at such general facilities can be predicted with a degree of accuracy. Through modelling and simulation, especially crowd behaviours at such facilities, we can accurately predict and optimally utilise the different sections, notably by identifying potential problems.

1.3 Motivation

Larger crowds, such as the ones attending religious or sport functions are harder to manage, and due to the collective forces of the crowd members dangerous incidents are more likely to happen in such crowds. Excessive densities are dangerous and should be averted, they cause crowd members to feel to less safe and more uncomfortable in denser crowds.

Being able to simulate crowd behaviour can aid in the efficient management and organization of these important events, putting preventive measures in place to help ensure the crowd members' safety while impeding deadly scenarios from occurring. Simulation helps to smooth out the crowd flow from within and outside of the area, by revising the design and arrangements where bottleneck takes place. Simulation models also help to increase the awareness of crowd dynamics. For example the new design of the Jamarat bridge (a pedestrian bridge used by Muslims during the Stoning of the Devil ritual in the last stage of the Hajj) has resulted in a great improvement of crowd movement over the bridge. As a result Hajj over the last few years had been completed without any major incidents, until the unfortunate stampede that took place in the area leading up to the Jamarat Bridge claiming the lives of over 750 pilgrims during the 2015 Hajj [8].

Case studies allow the analysis of real world problems of which one has experience or is able to observe, and have been shown to bring interesting real world situations into research. This thesis seeks to solve a real world problem; therefore, case studies are a very suitable research approach for this thesis. For efficient management of large crowds we want a case study that satisfies certain specifications, such as a large crowded area with a minimum crowd density of 6 persons/m^2 (in order to be considered as a high congestion area) [9], the event should be scheduled every year/month so that we can study a suggested solution for the subsequent events and busy places. Moreover, it should be general enough to be applied to other cases with a few customisation efforts. We have found that all of these criteria are applicable to The *Sa'yee* ritual; hence, it has been chosen as a case study for the thesis.

1.4 Research Objectives

For efficient management of large crowds and to improve the crowd members' performance it is vital to understand the dynamics of their behaviour. This calls for an urgent need to modelling and simulating a real case of a large crowd (e.g. Al-Masjid Al-Haram) so that is be more safer and friendly for people and especially the ones with disabilities. Hence to achieve these goals our research is based on the following objectives:

- Develop a consistent and integrative technique to identify, simulate and analyse crowd behaviour;

- Develop a general and flexible modelling framework that can be implemented on multiple agent-based simulation platforms;
- Propose a methodology to extract crowd characteristics from any unknown camera position;
- Develop a flexible, validated and customizable simulation model able to simulate different agent types in various scenarios and situations;
- Build a system that can cope with extreme situations, as well as normal densities;
- Study the effect of dedicated separate lane for the people with disabilities in the corridor.

1.5 Thesis Contributions

This section enumerates the thesis contributions, outlines the motivation and the work carried out in the thesis.

Contribution 1: Multiagent-based *Sa'yee* model

Motivation. We want to improve the crowd simulation and develop a more realistic approach in this simulation model for people walking in corridor. There are many approaches that can be taken to design and develop such a model. One of them can be by done by enhance the current models by improving the calibration and validation stages. The other can be to use new simulation platforms that support simulating large crowds in an effective way. By capturing significant crowd characteristics that are not captured by the current simulation models, the model can produce more accurate results by considering more behaviours. **Contribution.** We propose, design, and develop a realistic, flexible and general state-based model of the *Sa'yee* corridor. Due to the flexibilities provided by the ABM systems; the model designed is based on agents; can be mapped onto various agent-based systems; and has been implemented on an ABM platform called NetLogo. There are two enhancements carried out in the *Sa'yee* model, and simulations that make this research novel and different than other such research. The first is the addition of a diverse crowd population including disabled pilgrims, and the second is the use of real video recordings to analyse and model the physical behaviours of the pilgrims.

Contribution 2: Extraction of crowd characteristics from real-life videos

Motivation. Real CCTV recordings have been used to study the behaviours of the crowds at different facilities including Al-Masjid Al-Haram. These video recordings help to identify the different characteristics of groups and individuals in the crowd. These characteristics can be, overtaking, grouping, and walking with different speeds, etc. No previous research in this area uses real CCTV recordings to extract and study physical crowd behaviours, and most of their experiments were carried out in a lab based setting.
Contribution. We propose and develop a new technique for extracting crowd characteristics from real-life videos, that can be used for analysing and modelling the physical behaviours of members of the crowd at both macroscopic and microscopic levels.

Contribution 3: Model evaluation using real video recordings

Motivation. No model can claim that it fully represents the real system. We believe that a practical way to validate the accuracy of the model is to compare the simulation results against the data collected from the real system. For example, in our case we want to demonstrate that some aspects of the *Sa'yee* model proposed in this thesis match the real *Sa'yee* crowd behaviour.
Contribution. We conduct an experimental evaluation of the proposed model using real data obtained from videos of the ritual. We also provide a detailed evaluation of the validity of the proposed model, and present results with discussions and analysis of this evaluation. Based on the results of the empirical study we establish the following findings:

- The densities in the ends of the corridor are larger than those in the centre of the corridor;
- For the pilgrims who stay in groups for various reasons, such as the care of family members etc., the smaller (less than 10) groups are safer for all than the larger groups, because a group of more than 10 can become a barrier in the corridor, blocking the overtaking ability of the others;

- Pilgrims are much safer in the corridors performing the ritual without groups;
- The agents in a group tend to stay within the group and its leader, and the agents walking at a slower speed are overtaken by those walking at a higher speed.

1.6 Justification of the Research

As is clear from the above discussion (Section 1.3), the number of casualties due to congestion and stampedes at the Hajj rituals are increasing over time. The latest expansions of Al-Masjid Al-Haram and the crowd controlling techniques implemented, have solved some of the problems of congestion. However, there are still unsolved issues such as the pilgrims entering, exiting, and stopping at either end of the corridor before making the U-turn which further contributes to congestion. There is a need to model and simulate the Hajj rituals to decrease the casualties and help manage the crowd in an efficient way. There are two important rituals of Hajj ("is an Islamic terminology, it implies heading to Makkah to observe the rituals of pilgrimage." [10]):

- *Tawaf*: Circumambulation around *Kaabah* seven times[10];
- *Sa'yee*: Walking between two hills (*Safa* and *Marwah*) seven times.

Many studies [11–13] have been carried out to enhance the performance of the Hajj rituals, but most of them have focused on the *Tawaf* ritual while very few have concentrated on the *Sa'yee* ritual. The *Sa'yee* ritual takes place within a corridor joining the two hills *Safa* and *Marwah*. Pilgrims are required to move between these two hills seven times [14].

None of the current techniques [15–17], that focus mainly on crowd behaviours during the *Sa'yee* ritual, deal with disabled pilgrims. Relating the data from the simulation model with data from real-life helps analyse and validate the correctness of the simulation model. None of the previous studies included real-life data in order to analyse and model the behaviours of the pilgrims during the *Sa'yee* ritual.

We chose to model and simulate the *Sa'yee* ritual because; it is the second most crowded area during the Hajj, its simulation is a more generalized case and can be applied to any other crowded corridor. A simulation of the *Sa'yee* corridor will help us better understand the interactions, behaviours and movements of pilgrims in this area. This will also give us the capability to investigate the model and recommend measures to improve the throughput of the *Sa'yee* corridor and increase the pilgrims safety in this area.

Keeping these problems and motivations in view (see section 1.3), we develop new techniques and models to enhance the performance of the Hajj rituals.

1.7 Problem Analysis

Computer modelling and simulation are one of the essential methods for studying real world phenomena and many other associated problems. There are various types of research carried out in computer science, such as (1) empirical or experimental research, which includes surveys, statistics, questionnaires or field works; (2) theoretical research, which mainly involves the study of conceptual issues; (3) case study an analysis of real world problems of which one has experience or is able to observe.

Of these three types of research, case studies have been shown to bring interesting real world situations into the research; hence, case studies are a very suitable research approach when seeking to simulate social crowds. In this thesis, we have chosen one of the crowded areas, which meets certain criteria:

- A large crowded area with a minimum crowd density of 6 persons/m^2, as mentioned in many studies such as[18]. After this level, it will transform to a dangerous crowd;
- The crowd should occur occasionally, such as monthly or yearly, to be worth investigating;
- Has a general enough layout so that it can be applied to any other similar cases (in our case, we chose a corridor because of its ease of application and also owing to the fact that some of the parameters fit to other facilities);
- The area should be equipped with CCTV cameras or with surveillance facilities;
- Offer an access of CCTV recording facility.

The *Sa'yee* ritual (one of the Hajj rituals) satisfies all of the before mentioned requirements and specifications, hence it was selected as a case study for the thesis. Here, we introduce the *Sa'yee* ritual and explain why it is performed and the problems facing the individuals performing this ritual. Figure 1.1 shows the normal and peak times of *Sa'yee*. In order to explain what the *Sa'yee* encompasses, we need to first explain the Hajj, its rituals, and their significance.

FIGURE 1.1: A photo of Almas'a at peak time on right and at normal time on the left [19]

1.7.1 What is the Hajj and Why its Important?

Muslim pilgrims gather in *Makkah* at Al-Masjid Al-Haram in the Kingdom of Saudi Arabia to perform a set of rituals. These rituals are based on the ones conducted by the Prophet Muhammad during his last visit to the city of *Makkah*. Performing these rituals, known as the Hajj, is the most significant reflection of Islamic faith and unity. Performing the Hajj at least once, is a duty upon all Muslims who are physically capable and have sufficient finances that enable them to make the journey to *Makkah*. It is the duty of a Muslim to provide sufficient financial stability for his family prior to undertaking the Hajj. This in conjunction with the immense crowds and the intense heat present in most Hajj seasons makes for a very taxing pilgrimage, and can lead to dehydration and extreme physical exhaustion during the performance of the rituals. Therefore, the requirement that a Muslim be healthy and physically capable of undertaking the pilgrimage is intended to exempt those who are not capable of enduring the rigour of extended travel and the Hajj [20] . It is the dream of every Muslim to perform the pilgrimage at least once in his life time, and is considered to be pinnacle of a Muslim's life. The lesser pilgrimage, Umrah can be performed at any point during the calender year. The greater pilgrimage, Hajj can only be observed during a five-day period starting from the ninth and ending on the thirteenth day of Dhul Al-Hijjah, the twelfth month of the Muslim lunar calendar. Every year more than two million people perform the Hajj pilgrimage (Figure 1.2).

FIGURE 1.2: A photo of Al-Masjid Al-Haram at the maximum crowd time [21]

1.7.2 Why Muslims Go to Hajj?

Muslims, the followers of Islam, which is the second largest and the fastest growing religion in the world, believe that there is only one God (Allah) in existence for all life and the Hereafter, who has created everything. Humans in particular have been created to worship and obey Allah, as taught to them by the Prophets of Allah. These Prophets began with Prophet Adam who was the first human on Earth, and ended with Prophet Muhammad (peace be upon him) [22].

Muslims are required to follow the commands of Allah based on the Quran (original book in Arabic unchanged since revealed over 1439 years ago) and the teachings of Prophet Muhammad (peace be upon him) as collected by early scholars of Islam. These two sources of guidance form the foundation for how Muslims must live their lives. The basis of this foundation includes the five pillars of Islam, wherein the last pillar is to perform the Hajj pilgrimage [23].

1.7.3 Researches in Hajj

Makkah crowds are regarded as being far more complicated than traditional crowds owing to the ethnic and cultural diversity of the people owing to the distribution of Muslims across the globe [24]. Importantly, this means the presence of different habits and behaviours in terms of walking speeds, for example, which may be a factor that has been neglected in a number of commercial simulation instruments, such as those detailed in [25],[26] and [27].For example average speed for normal walking of Americans male is 5.148 Km/h while it is 4.356 Km/h on Kuwaiti male [28]. Furthermore, the precision offered by any simulation framework can be affected by pedestrian social group behaviours [29].

All of these issues of crowd management, combined with many other factors, such as controlling the spread of disease, security, safety and transportation, have made establishing a research centre focused on Hajj a necessity for this area. The government of Saudi Arabia has dedicated a special institute to studying all topics related to Hajj and therefore supports researchers in this field with the aim of improving the experience of Hajj. The Custodian of the Two Holy Mosques Institute of the Hajj Research (CTHMIHR) was established in 1975 with the objective to improve the experience of Hajj and improve safety for all pilgrims, as a consultant authority for the High Committee of Hajj and other authorities working in Hajj affairs. The principle goal of CTHMIHR was focused on establishing a statistics/data hub that provides information about Hajj. This hub of information functions as a source of inclusive scientific reference, providing various aspects, namely statistics, details and facts. This, in turn, facilitates the planning of services and utilities available throughout the period of pilgrimage[30].

Researches and development of the areas of Hajj activities required to provide a safe, healthy, and satisfying Hajj experience within the strict Hajj time-line [31] . In accordance with the substantial increases in the Muslim population over the past several decades, the number of pilgrims performing Hajj has increased significantly [32]. This massive influx of pilgrims has rendered the current facilities and policies inadequate to handle the large movement of pilgrims, between Hajj related sites and the individual Hajj rituals. Earlier studies have resulted in many sophisticated and expensive for example, the latest expansion project had been cost more than 22 billion US Dollar [33]. Nevertheless, carrying-over such research projects is very essential for several reasons.

First, there have been many casualties over the years due to uncontrolled crowd movement at the *Tawaf* and Jamarat areas, which has resulted in serious injuries and many fatalities to hundreds of pilgrims. Second, due to the large number of pilgrims arriving from all corners of the world, many diseases have been spread during Hajj and then dispersed back in the pilgrims' home countries upon their return. Third, as the number of pilgrims performing Hajj increases every year, the congestion of the existing facilities is further exacerbated to the point that health and safety becomes a very serious concern for some Hajj sites due to continually increased over crowding. As such, it is equally essential to not only keep expanding the Hajj sites, but to better manage the current Hajj sites. This will enable them to adequately accommodate the steadily increasing number of annual pilgrims, through better planning and clearly defined polices that will help to ensure the health and safety of all pilgrims. Thus, it is crucial to continually research the Hajj process and improve the Hajj crowd management process. provide all the resources necessary to service pilgrims and facilitate the Hajj performance [34]. Accordingly, it is essential to increase resources through the continual study of new and existing issues related to the pilgrimage and the services provided. This in turn will determine any possible problems and issues; as well as provide solutions based on scientific methods.

In the current project carried out in this thesis, the Custodian of the Two Holy Mosques Institute of the Hajj Research provided access to part of its database of surveillance camera recordings for Almas'a corridor. They also allowed the acquisition of an electronic copy of the corridor layout, which facilitated the building of our simulation environment reliant upon on the accurate information provided.

1.7.4 Hajj Activities

The annual Hajj occurs during the 8th to 13th days of Dhul-Hijjah of the Islamic Lunar Calendar. Figure 1.3 presented a diagram of the Hajj activities. The key six steps of Hajj are primarily [35]:

- Prior to Hajj (Perform Visiting *Tawaf* and *Sa'yee*)

  Upon arrival in The Kingdom of Saudi Arabia, pilgrims proceed directly to *Makkah* stopping briefly at one of the designated areas outside of *Makkah* to bathe and

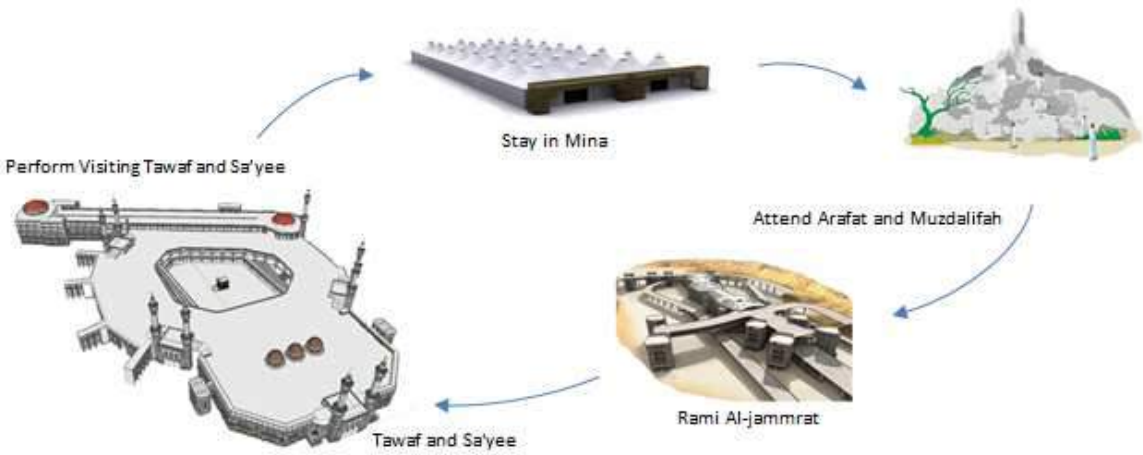


Figure 1.3: Hajj activities

change into their pilgrimage clothing prior to entering the city. Once inside the city limits the pilgrims continue towards Al-Masjid Al-Haram, entering by the As-Salam Gate. They pass the *Sa'yee* ritual area, making their way towards the *Kaabah* in the centre of the Mosque to begin the *Tawaf* ritual. Pilgrims start *Tawaf* at the corner of the *Kaabah* closest to the *Safa* hill in the *Sa'yee* ritual area and circle around the *Kaabah* in a counter clockwise direction 7 times. To accommodate the vast crowds *Tawaf* may be completed from any of the three levels provided around the *Kaabah* area. After the completion of the *Tawaf* ritual pilgrims pray facing the *Kaabah*, and then proceed to the *Sa'yee* ritual area which is enclosed inside the grand mosque complex. Pilgrims begin the *Sa'yee* ritual at the *Safa* end of the Ritual area, walking 7 times between the two small hills, *Safa* and *Marwah* thus completing the ritual [35].

- Day 1 of Hajj (Stay in Mina)

  The first day of Hajj commences with millions of pilgrims beginning the four to five kilometre trek to Mina, an area located in the east of *Makkah*. The pilgrims are required to reach their destination prior to the Dhuhr (Noon) Prayer. Once in Mina they will be provided shelter in one of the more than one hundred thousand air-conditioned tents in the encampment area, spending the rest of the day performing their prayers and reciting Quran, preparing themselves for the next leg of their pilgrimage in the morning [35].

- Day 2 of Hajj (Attend Arafat and Muzdalifah)

  The second day of Hajj begins with pilgrims offering their morning prayers and setting off on the longest leg of their journey after dawn. Hajj pilgrims numbering into the millions will then undertake a fifteen to sixteen kilometre journey, arriving at the plains of Arafat where they will spend the day standing or sitting near the mount of mercy. Here pilgrims make Dua (supplication) to Allah for forgiveness of all their transgressions in life, and pray for their Dua's acceptance. At dusk after the Magrib prayer pilgrims will once again start making their way towards *Makkah*, where they will spend the night in Muzdelifah approximately half way between Arafat and Mina. While in Muzdalifah, pilgrims continue their supplications while gathering small bean sized pebbles in preparation for the final Hajj ritual the next day [35].

- Day 3 of Hajj (Day of Eid)

  In This day the pilgrims ready themselves to leave before sunrise to Mina where they perform the Jamarat ritual. Upon arrival in Mina the pilgrims will pray the noon prayer and then make their way to the three pillars; Al-Aqabah (large), Al-Wusta (medium), and Al-Sughra (small). When they arrive at the designated areas, they throw seven of the pebbles they gathered in Muzdalifah successively at each of the three pillars in an ascending order. This symbolic stoning is in remembrance of how the Shaytan (the Devil) endeavours to tempt humans in their daily lives, as he tried to tempt the Prophet Ibrahim (Abraham) to defy Allah. The Prophet rebuked the Shaytan each of the three times he appeared to him, by pelting him with pebbles, and was rewarded by Allah for his obedience. Once the final ritual has been completed pilgrims enjoy three days of rest and Eid celebrations [35].

- Days 4, 5, and 6 of Hajj (Rituals in Mina (Rami Al-Jamarat))

  Once the Jamarat ritual has been completed, Muslims slaughter a sacrifice of which they will keep one third, gift one third to any friend or relative, and give one third to the poor. The slaughter can take place from the tenth to the thirteenth day of Dhul Al-Hijjah, but not after that time. After the Hajj is complete pilgrims will cut their hair; the men shave their heads and trim their beards, while the women will cut only a finger tips length off the ends. Pilgrims are not allowed to cut their hair until their sacrifice has been given and received. During this time pilgrims will feast and celebrate the completion of their Hajj rituals [35].

- Perform *Tawaf* and *Sa'yee* (Farewell *Tawaf*).

  The last ritual to be performed is the Farewell *Tawaf*. This can be done at any time prior to leaving *Makkah*. As in the Visiting *Tawaf* ritual, pilgrims will once again circumambulate seven times in a counter clockwise direction around the *Kaabah*. Pilgrims also then have the option to perform *Sa'yee* again, depending on whether or not they performed the *Sa'yee* ritual when they first entered *Makkah*. For pilgrims the Farewell *Tawaf* can bring about a vast array of emotions; from a euphoric elation for having successfully complete the Hajj, to an intense sadness and a sense of grief that they have reached the end of their pilgrimage. A vast majority of the pilgrims struggled and toiled for years to be able to come on this monumental journey, making *Makkah* the journey of a lifetime, and they leave knowing they will never see the *Kaabah* again [35].

In this thesis we focus on *Sa'yee* ritual only, and the following Section describes this ritual in more detail.

1.7.5 *Sa'yee*

Sa'yee is an Islamic ritual and it is one of the Hajj activities. The pilgrim should complete seven laps between two hills *Safa* and *Marwah* strating from *Safa* [36] It is takes place in the long corridor (known as Almas'a) a part of the holy mosque in *Makkah* (Al-Masjid Al Haram). The area of Al-Masjid Al Haram borders the *Kaabah*, which is the location to which Muslims from across the globe turn when carrying out their daily prayers. It is recognized as being the largest mosque in the world, and from an Islamic point of view is considered to be the holiest place. The prophet Ibrahim was instructed by God to place his wife Hajar (Hagar) and their infant son Ismail (Ishmael) in the desert. This place was situated between *Safa* and Al-Marwah hills. They were only given basic provisions to test their faith. When their provisions were depleted, Hajar began to seek help and search for water. To enable her to complete her quest quickly, she left her son on the ground and went alone. Climbing *Safa*, the nearest hill, she looked over the surrounding area. Upon seeing nothing, she went to *Marwah*, the other hill, to search further. Hajar was able to see Ismail and know he was safe, while she was on either hillside. However, she would run in the valley as she was unable to see her son, and would therefore walk at a normal pace when on the hillsides while her son was in view. Hajar returned to her son after travelling back and forth seven times between the hills in the fierce heat. Upon her return, she discovered that the crying baby, i.e. her son, kicked the sand with his feet and a spring was pouring forth under his feet. As a reward for Hajar's patience and sustenance for both, this spring called the Zamzam Well was revealed by the angel of God[35].

A high density crowd of people from all over the world come to Mecca (*Makkah*) to perform the Hajj ritual. This ritual requires the pilgrims to perform several steps. The pilgrims have to accomplish a specific activity at each step. For the purpose of the work carried out in this thesis we have focused on the *Sa'yee* ritual. The *Sa'yee* ritual takes place between the two hills, the *Safa* (or *As-Safa*) and the *Marwah* (or *Al-Marwah*), linked by a corridor. Beginning at the *Safa* end of the corridor every pilgrim is obliged to walk between the hills seven times, ending at the *Marwah* end.

1.7.5.1 The Corridor(Al-mas'a) Description

The corridor in *Makkah* (Al-mas'a) is considered the longest corridor of its kind in the world [37], a length of 394.5m and width of 40m,of which the main straight area is about 300m, with approximately 45m being used for turning at either end. The straight part of the corridor has different lanes: for able bodied and disabled pilgrims. The corridor has a total width of 40m comprised of 17m width lanes for the able bodied, and 2.5m width lanes which are dedicated for the usage of disabled pilgrims (see figure 1.4 in) and their accompanying groups [37]. If a disabled lane is at a lower capacity, and in order to transfer the load in the other lanes, some of the able bodied people also use this lane. Disabled pilgrims are provided with two priority lanes, one for each direction. These lanes are situated in the most enclosed part of the corridor. At either end of the corridor the pilgrims have to change the lane in the turning area. The marble used to tile the floors, is carried through to the walls reaching the level of the windows in the corridor. There can be either single individuals or groups of pilgrims walking in each lane. Unless the need arises to overtake others the pilgrims generally move in a straight line. Pilgrims need to avoid a few obstacles, such as pillars at either end of the corridor. A floor outline of the corridor is shown in Figure 1.5.

FIGURE 1.4: Disabled priority lanes depicted on the right [30].

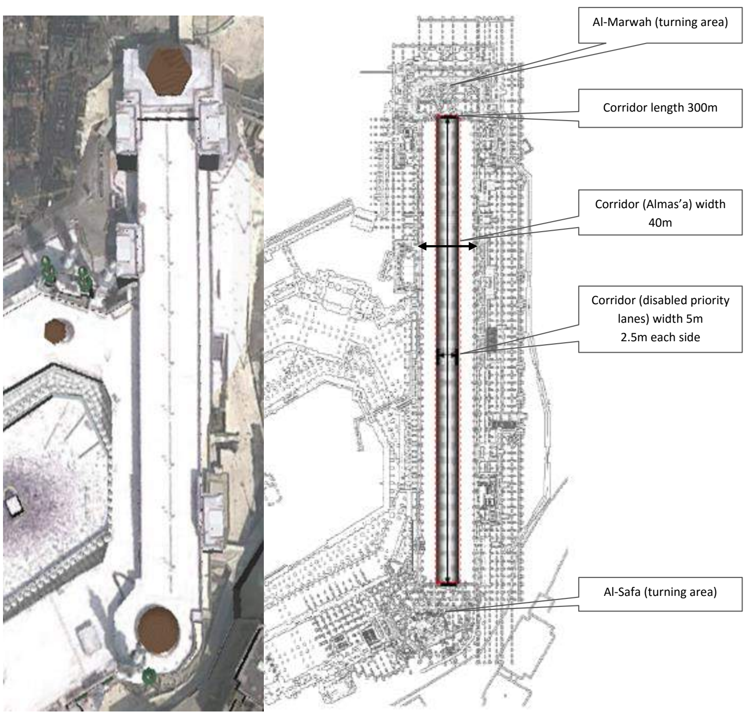


FIGURE 1.5: A live photo of the corridor from Google Earth [38], on the right its dimensions

1.7.5.2 How to Perform *Sa'yee*

Sa'yee is a decisive movement, and is represented by running and hurrying between the two hills. During *Sa'yee* people act as Hajar had acted while she was looking for water.

- Start from Al-safa;

- Facing the *Kaabah* and raising the hands and say the Dua (supplication);
- Proceed to Al Marwah;
- Return back to As-Safa
- Continue this task until the seven rounds are completed.

The going from *Safa* to *Marwah* is a round and returning is another round.

1.7.5.3 The Major Issues in the Corridor

Due to the large increase in the number of pilgrims crowd management techniques have become essential, requiring the rituals to become more formalized. The Almas'a corridor has four floors, so the pilgrims can perform their *Sa'yee* ritual in any one of its floors. and the latest expansion that was made following the orders of the custodian of the two holy mosques Abdullah Bin Abdulaziz in 2008 solved a big part of Almas'a crowd congestion issues, by increasing its capacity from 44000 worshippers per hour to 118000 worshippers per hour [39]. However, there are still issues such as stopping at either end of the corridor before making the U-turn to point at *Kaabah* on each lap. This stop is unnecessary as people can carry on walking, while pointing to the *Kaabah* at the U-turn. Many incidents still occur during the Hajj rituals, even with the current crowd management techniques, as pilgrims are injured in a stampede, or ramps collapsing under the massive weight of the many pilgrims, causing hundreds of deaths. The website of the Kingdom of Saudi Arabia's Ministry of Hajj displays a message, "Be peaceful, orderly and kind. No crushing" [40].

Crowd congestion is produced by pilgrims' movements within the peak hours, particularly throughout the Ramadan season and the Hajj. This congestion forces pilgrims to travel and move in different directions simultaneously. The most significant factors that impact these rituals are [41]:

- The geometry of the *Mataf* area (Figure 1.6);
- The location of key historical and ritual attractions;
- Certain behaviours adopted by pilgrims, including chain-like movements and clustering.

And we may also include:

- The size of the crowd gathered, containing in particular a high number of disabled individuals, as well as family and peer groups;
- The annual recurrence of the event, which allows us to make and test simulation hypotheses, and gather further real world evidence.

FIGURE 1.6: *Tawaf* view within the region of Mataf, [41].

In particular, congestion at bottlenecks can cause pilgrims to move in conflicting directions simultaneously making the risk of collision extremely high. This is further complicated by the heterogeneous nature of the population, since different groups of pilgrims move in different ways and by different means (quickly vs slowly; individuals vs groups; foot vs wheelchair). The development of appropriate models is essential to help identify triggers for key behaviours within dense crowds, e.g., trampling, falling, collisions, pushing, etc. This is especially important, because such groups can act as obstacles in their own right necessitating the ability to simulate the various groups of pilgrims within the crowd.

Here it is worth noting the problem of validation – how do we know whether a simulation gives a reliable approximation to real-world behaviours? Current research relies on the analysis of video footage in order to identify real-world parameters against which simulations could be compared [42], e.g., paths followed by family members can be expected to cluster more than those of strangers. This task has been greatly simplified by the advent of modern technologies. For example, [43] used a variety of Geographic Information Systems (GIS) and Global Positioning Systems (GPS) to monitor the movement of pedestrians performing *Tawaf*, and then used tracking-analysis software to analyse and visualize pilgrim movement patterns. As well as providing historical data for benchmark purposes, this kind of approach can be seen as a possible alternative to simulation, since it helps reveal real-world patterns that can act as a framework for future enhancements to the urban and architectural environment.

The development of a software model is necessary to simulate the behaviour of members within dense crowds like; trampling, falling, collision, pushing, etc. The ability to simulate a group of pedestrians is also significant because this group may become an obstacle to the movement of other pedestrians. The area of *Tawaf* and *Sa'yee* are one of the most popular places that include this phenomenon. Thus, a suitable software with appropriate microscopic navigation should be used to model these rituals. The capabilities of navigation and path design can help simulate specific patterns of movement, like the various actions of pilgrimage within *Tawaf* and *Sa'yee*. There are many features that help to manage the crowd movement, such as; the knowledge and communication that is conveyed among agents and learning and mental maps used by the agents, etc. [44].

1.8 Thesis Overview

The rest of the thesis is organized as follows:

Chapter 2 Discusses the related work, previous research carried out in the crowd modelling arena, and reviews all other techniques and methods.

Chapter 3 Discusses and gives a background on the methods used to extract crowd characteristics, the modelling approach, programming languages, tools and implementation used in this thesis. In addition, a description of the software tools used to reproduce the work is also discussed.

Chapter 4 Demonstrates the results of all experiments and presents the results with interpretation of them.

Chapter 5 Concludes the thesis and lessons learned to improve crowd management and accordingly minimise risks. Ends with discussion of the future work that can be carried out.

Chapter 2

Literature Review

2.1 Introduction

To establish successful research in any topic, it is mandatory to cover the state of the art of your topic in order to identify gaps in the current work and avoid wasting time and effort on research already conducted or problems solved. It is an essential step to explore what has been done and what needs to be considered. This allows you to build up your research from the last point covered.

In this chapter, the most recent works in the field of modelling and simulation social crowds have been considered, including all required tools, techniques and knowledge in building a crowd simulation model. To make this chapter easier to read, it has been divided into four sections:

- Crowd definitions and related issues.
- Simulation and modelling social dynamics techniques and tools.
- Modelling and simulation Hajj activities.
- Modelling and simulation *Sa'yee* ritual.

2.2 Social Crowd

2.2.1 What is a Crowd?

The completion of a literature review highlights no specific definitions pertaining to the concept of a crowd; more specifically, there are a number of definitions identified, all of which have their own specific behaviours and characteristics. A number of other researchers have made use of definitions for 'crowd', all of which are seen to have in common various features, such as conceptualising a crowd as comprising a large number of people at a specific location for a particular period of time, and demonstrating particular behaviours and goals [45, 46]. In these papers, a more clearer understanding of the term is utilised. The following is adopted throughout the thesis [47]:

A large group of heterogeneous individuals present in a common physical environment sharing a common goal. Crowd members may act differently when they are alone or in a small group. [45].

The definition of Duives et al. [45] has been used as the formal meaning in this context

'A crowd is a large group of individuals (N $\geq$ 100 persons) within the same space and at the same time where the d $\leq$ 8).'

Where N is number of agents, and d is density.

Still [18] determined the crowd risky level. Figure 2.1 shows the crowd started to be risky when the density exceed 5 person/m^2.

2.2.1.1 Types of Crowds

In order to successfully manage a crowd and improve the performance of the crowd members, it is very important to distinguish distinct crowd types at a particular event and within a larger crowd. There are a range of crowd types, with no specific singular type, consisting of their own characteristics and behaviours. There is not much research done into crowd types. Some of the crowd types identified by Berlonghi in [48] are as follows:

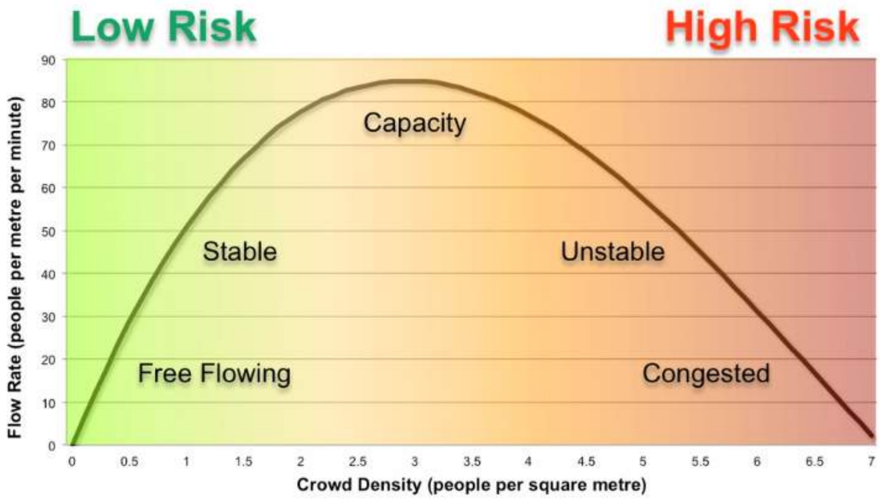


FIGURE 2.1: Crowd risky level measured by person/m^2 Still [18]

- Spectator crowd – A crowd observing an event that they have come to see at a venue, or which was occurring upon their arrival at the venue.
- Demonstrator crowd – A crowd that pickets, demonstrates, marches, or chants, and is organized for a specific reason or event, often with an identifiable leader.
- Dense or suffocating crowd – A crowd where physical movement of the people rapidly decreases – to the point of futility – caused by excessive crowd density, with people being carried along and squeezed, resulting in fatalities and serious injuries from asphyxiation.
- Violent crowd – A crowd terrorizing, rioting or attacking, with no respect for the law or the rights of other people.
- Escaping crowd – A crowd endeavouring to escape from life-threatening situations, such as a perceived or real danger. This may include individuals involved in an organized evacuation, or disorganized pushing and shoving by a stampeding mob.

The crowds at Hajj pilgrimage are gathered for a specific reason, members of the crowd are often led by a leader, and are large in numbers with high density, and therefore can be identified as *Demonstrator and Dense crowds.* The members of such a crowd type at Hajj pilgrimage possess the following characteristics (types):

- Members who are totally compliant. They are passionate and do not cause trouble.

- Members who commit anarchy when pushed by other members and becoming caught up with the passion of the crowd.

- Members walk at a speed that is determined by the density of neighbouring members, the behavioural characteristics of the members, and the ground on which they walk. Members will seek to minimize the predicted travel time but may be tempered by a desire to avoid extreme densities.

- Members have a mutual understanding of the task (called potential) that is required to reach their mutual destination, such that any two members having the same capability at various locations would perceive no leverage in swapping places. This is true only if a visual assessment of the situation is possible. In case, there is a variation in the height of the members, then a tall member can block the view of a shorter member, and the shorter member must obtain information about the desired direction of motion from observing the behaviour of the taller members in the crowd.

2.2.1.2 Collective Phenomena in Crowd Dynamics

Dynamics of crowd behaviour and movement depend on various factors, such as average speed, volume and density of the crowd, human emotions such as excitement, fear and religious fervour, physical attributes of the space, etc. These dynamics exhibit a variety of fascinating and surprising collective phenomena. The most known of them discussed in the literature [49–54] are:

- *Lane formation*: One of the most fundamental and commonly seen elements of bi-directional streams. This predisposition of pedestrians to walk behind one another and to create lanes helps to circumvent collisions and further helps to enhance speed. At low density members of the crowd favour walking side-by-side developing a lane orthogonal to the walking direction, hence covering a significant area in the walking space. When the congestion level escalates members of a crowd form a 'V'-like or 'U'-like walking pattern with a group of three or four members, in an attempt to adapt to the reduced availability of space.

- *Oscillations at bottlenecks*: Bottlenecks are a significant priority in the calculation of a facility's evacuation times and other observables. This strongly suggests the necessity for thoroughly understanding the anomalies that develop in junctions with bottlenecks, in order to create reliable simulation models of the crowd members' movements. Oscillations arise when members are seen to compete with others moving in opposite ways, with both groups seeking to move through the same bottleneck. This is recognised by the flow direction fluctuations, in different time intervals.

- *The faster-is-slower effect*: Trying to move faster can cause a smaller average speed of leaving, because clogging is connected with delays, and this is called the faster-is-slower effect. In a crowd the shared desire to leave a room or space is known to go hand-in-hand with the greater inclination of members to become stacked, thus preventing them from leaving and restricting the evacuation time. Due to the faster-is-slower effect, panics can be triggered and can cause delays to the crowd members intending to leave. This causes the other members in the back to become impatient and pushy, as they are unaware of the reason for the temporary slowdown.

- *Clogging at exit*: Whenever two or more members of the crowd, move to, or, compete for, the same place, clogging can occur. Clogging at exit is seen through the circular clustering of a crowd at an exit location and can highly increase the evacuation or exit time, and is very common in larger crowds. These phenomena, can cause uneven exit rates which prevents smooth passage along the exit width, and are interesting for studying and simulating due to the fact that they are the most frequently witnessed behaviour in crowd dynamics.

2.2.1.3 Examples of Crowds

Large gatherings of pedestrians are found in closed facilities like shopping malls, stadiums, markets, and in open facilities like walkways and parks. These gatherings are massive and have a purpose, and therefore can effect the structure, design and management of these facilities. For example, most of the shoppers in a mall would like to window shop, whereas pedestrians in a street would like to reach their destinations faster compared to the shoppers in a mall. These pedestrians may have an average speed that is higher than a shopper walking in a mall. The size and density of a crowd also plays an important role. Larger crowds (e.g. religious or sport functions) are more difficult to manage. The combined forces of pedestrians in these gatherings/crowds have more chances of causing dangerous incidents. Members of these gatherings/crowds feel less comfortable. Therefore, excessive congestion is dangerous and should be avoided. For safety of the crowd members, one of the studies [55] recommended the maximum density of 4 pedestrians per square meter. The following Sections introduce two specific cases of a crowd. The first case is about a large crowd at a Muslim mosque in Saudi Arabia where millions of people gather to perform their pilgrimage showing general nature of religious crowd.The second case in this thesis is about a representative crowd of a Shopping mall that shows the general crowd behavior.[14].

2.3 Simulation and Modelling Techniques and Tools

In this section, we highlight a variety of tools and techniques that have been applied by the researcher to model and simulate social crowd dynamics. In the following sections, a number of descriptions are provided relating to each of the most commonly used tools and techniques in line with the research topic.

2.3.1 Crowd Modelling and Simulation Techniques

Many fields such as safety engineering, architectural design, military simulation and digital entertainment, to name a few, have key design issues which necessitates the use of modelling and simulation. Crowd simulations have become a corner stone in real-time tactical military instruction. In recent years, modelling and crowd simulation have been achieving astounding momentum in examining pedestrian dynamics.

Numerous simulation techniques have been designed and implemented to produce the behaviour of pedestrians in a crowd. Various behaviour models have been suggested with diverse types of modelling techniques being used, such as agent-based models and force-based models. To reproduce the crowd dynamics for research purposes, modellers have studied and examined a number of social factors, physical factors, and psychological factors when symbolizing crowds in their models. Crowd models may also incorporate different facets of a crowd. Some of the work targets the *extraneous attributes* of a crowd, such as poses, movement patterns, appearance, and coordinated positions of individuals; and some other work targets how a crowd's social behaviours emerge over time consequent to some events.

Current research done on the existing models simulated of thousands (huge-sized), hundreds (medium-sized), or tens (small-sized) of individuals. Types of techniques applied when modelling a crowd are based upon crowd volumes. When dealing with excessive crowd congestion the existing work focuses on the crowd as a whole, giving more preference to the global trend of the crowd, because of the exorbitant computational cost. This is not the case when modelling small to medium-sized crowds, and therefore the current research is able to implement the individual behaviours in the crowd model in such cases. This also allows the researchers to introduce more details into the crowd model, and facilitate the study of crowd dynamics at an individual level.

Most of the work related to crowd modelling focuses either on long-term or short-term crowd simulations. Some of the examples of long-term crowd simulations include the examination of how opinions of people are stirred by various aspects, and how fundamental theories are composed and transmitted among the crowd individuals [56, 57]. The basic process for these simulations has a comparatively long time period. In contrast, research into short-term crowd simulation targets crowd behaviour on a short-term basis. This is achieved through investigating how a crowd will react to different incidents such as emergencies and threats; given the crowd formation, the social, psychological, and physical attributes of the individuals and groups in the crowd. The time scale of the crowd simulations of interest is generally in the order of minutes to hours [58].

In the following section, we listed the recent ABM modelling techniques used to model crowd behaviours.

2.3.1.1 Agent-Based Modelling and Simulation (ABMS)

Agent-Based Modelling (ABM) and Multi-Agent Simulation (MAS) [59] is a relatively new approach to modelling complex systems composed of interacting and autonomous agents, such as found in the *Sa'yee* ritual. The behaviours of agents in a system are described by simple rules and interactions with other agents in the system. These rules and interactions then in turn influence their behaviours. Agents can be modelled individually or in groups. This enables a user to model the behaviour of the system as a whole, and hence makes it easier for the user to observe the complete effects of the multiformity that exists among agents in their characteristics and behaviours.

The two distinguishing features of ABM that makes it different than other simulation techniques are ability to model heterogeneous agents across a populace, and the development of self-organization. These two features are also the reasons for selecting ABM to model the *Sa'yee* ritual in our thesis.

The flexibility of Agent Based Modelling (ABM) makes it one of the top contenders among other such simulation techniques. Its flexibility can be observed along multiple dimensions. As an example, it is easier to include additional agents to an agent-based model. To tune the complexity of the agents in a model, such as behaviour, degree of rationality, the ability to learn and evolve, and the rules of interactions, ABM provides a natural framework for the model. Another flexibility provided by ABM is the ability to alter the levels of specification and composition. For example, one can change the composition of all types of agents, like subgroups of agents, and single agents etc, with various levels of specifications in the same model. ABM can be used where the specification and composition of the model is not known ahead of time, and finding it requires some effort.

ABM enables a user to describe a system in its natural form, and in most of the cases is very well suited to specify and simulate a system composed of behavioural entities. This lets the user design and develop a model that is very close to reality. For example working of an organization, a traffic jam, the behaviour of voters in an election or stock market brokers, etc, can be modelled. ABM lets the user model the practicality of real-life, such as one can describe how shoppers move in a market or a mall than to come up with the equations that depict the dynamics of the shoppers density. Moreover, ABM can be applied in various areas such as:

- Flows: management of crowd, evacuation and traffic flows.
- Markets: simulation of stock markets, malls and shoppers.
- Organizations: design and working of organizations and the operational risks involved.
- Diffusion: diffusion of innovation and dynamics of adoption [5].

The flexibility of ABM allows it to be implemented either: using general all-purpose software or programming languages; or using specially designed software and toolkits, that can be used to address the specific requirements of agent modelling. Implementations of ABM can run from a small device to a large-scale computing cluster and in between, such as a desktop or a server [60]. A classic ABM has 3 elements [59]:

- A set of *agents*, each having similar or different characteristics and behaviours.
- A set of agent *relationships* and mode of interactions. These implicit properties of relatedness defines how, when. where and with whom agents interact.
- The *agents'* environment. Agents interact with each other, and also with their environments.

The ABM and MAS can be developed by programming, modelling and identifying all components of MAS. Furthermore, to run the model an engine of computation is required so that we can simulate the interactions and behaviours of the agent. This capability is also provided by other implementations like: programming and agent that is based on tool kit. The simulation can be run by implementing the agents, their interactions and behaviours. Then, the results are verified for correctness and validated to make sure they represented the real system accurately. Finally outcomes are obtained with recommendations and conclusion.

For a practical modelling standpoint [59] the following characteristics of an agent are described:

- An agent is a self-contained and uniquely identifiable individual.
- An agent is autonomous and self-directed.
- An agent has a state that varies over time.
- An agent is social consisting of some of the human characteristics and are capable of having dynamic interactions with other agents that in turn can influence actions and behaviours of the agent.
- An agent may be part of a heterogeneous population.
- An agent may be adaptive, and can modify its behaviours.

- An agent may be goal directed, i.e. having goals with respect to its behaviours.
- An agent may die or reproduce.

In an ABM, an agent has attributes and methods as described above. An attribute can be static, not changing during the simulation, or dynamic, changing during the simulation. Agents commonly communicate with a subset of other agents, called agent's neighbours. This neighbourhood is defined as agent spaces in the model. The environments may constrain an agent actions. For example a transportation model includes the capacities of the links in the road network, that limit the number of agents moving through the links in turn causing congestion effects.

Based on the attributes of an agent in an ABM, we specify the following criteria of a system (case study) that can be modelled using an ABM.

- A system where decisions and behaviours can be defined within boundaries.
- A system where the members adapt and change their behaviour and can engage in dynamic behaviours with the other members.
- A system where the members have dynamic relationships, i.e, the relationship can be formed and dissolved.
- A system where the members can form organizations, and can adapt and learn at this level.
- A system where behaviours and interactions of the members have a contiguous property.
- A system that can be scaled up to arbitrary levels[61].

The *Sa'yee* ritual as a case study satisfies the above specifications, and therefore we selected ABM to implement and simulate its model (see section 1.7). Further, the heterogeneous nature of a religious crowd calls specifically for the ABM platform. Also, it is easier to simulate and track agent behaviour and parameters like speed and density using the ABM platform

2.3.1.2 Using Agent-Based Modelling to Solve Crowd Problems

There are many studies performed to simulate and model the behaviour of pedestrians in different situations. One of these studies is the study of [62], which was based on using the PeTrack [63] software to gather trajectories from a wide experimental series involving a huge number of individuals. This software had the ability to extract the trajectories from the standard video recordings in an automatic way and with high precision in time and space. The conducted experiment was made to gather the trajectories in a highly accurate way in order to study pedestrian crowd dynamics. Furthermore, 99 runs were distributed throughout five days to test the dynamics of 250 individuals. The data reliability generated was enough to confirm the models at a microscopic level and to analyse the characteristics of the pedestrian crowd.

A real-time system had been presented in [64] to detect the crowd movement within a sequence of video. A scheme concerned with the crowd motion patterns within the domain of spatial-temporal was suggested. Furthermore, this scheme offered an effective implementation to reveal the crowd within effective-time. The suggested scheme was able to reveal the crowd at 70m distance or more. A video camera with progressive scanning had been used and was able to capture about 30 frames in each second with 320 x 240 pixels resolution. Moreover, the camera was fixed on various vehicles, where the camera height from the ground was only required to be known.

A data-driven method had been presented in [65] to simulate the virtual human crowd, that portrays actual traditional human crowd behaviours. A camcorder had been used to record the human crowd motion from an aerial vision. Then, two-dimensional trajectories of moving individuals within the crowd were extracted to learn the model of an agent that were produced by the trajectories. A group of videos had been extracted where these videos contained various behavioural patterns involving; wandering tourists, relaxed strollers and busy commuters styles. The key advantage of this technique was the capability to re-generate the realistic behaviours of the human group within the simulation environment.

The methods above, modelled the virtual human crowd where the number of pedestrians involved within the study is not large. Furthermore, the specifications of the camera used within these studies was identified. On the other hand, the methodology used in this thesis aims to simulate the behaviour of pedestrians while performing the

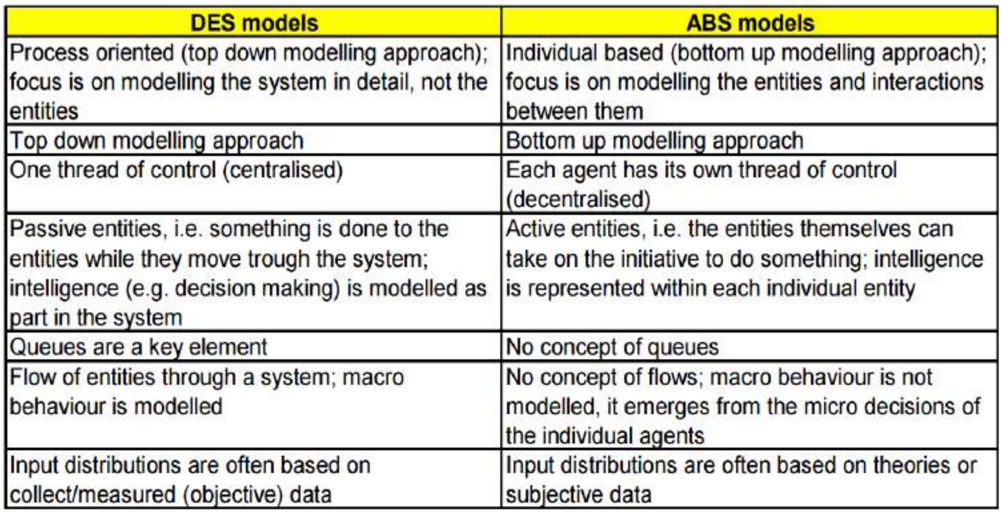
Sa'yee ritual. This methodology is based on collecting, extracting, modelling and then result validation. The NetLogo programming language is used to model the design. Furthermore, this methodology is different from other methodologies because it includes different types of pedestrians, and studies the behaviours of individuals and groups.

In addition, involving the disabled pedestrians within this work is an enhancement, where as they are not involved within any other study. The use of actual video recording within this study is the key enhancement from the other studies, and has been employed in three places to ensure the accuracy of the results. The types of cameras and the angles used while taking the photos are not known. In order to confirm the accuracy of the results, the specifications of pedestrian behaviours were measured in three different places ; Al-Masjid Al-Haram, Meadowhall Mall and the Hicks building at the University of Sheffield. We described this methodology in the following sections.

2.3.1.3 Discrete Events Simulation(DES)

A Discrete Event System defined as a system in which there is the occurrence of state changes/events at discrete points in time, with events taking no time to occur. There is the assumption that nothing of note occurs between two consecutive events; in other words, there is no state change recognisable in the system between the events. Such systems that are considered Discrete Event Systems may be devised through the application of Discrete Event Simulation. It should be noted that what may be defined as 'interesting' events and states ultimately depends on the goal and person of the individual performing the modelling [66]. In this vein, Siebers et al. [67] contrasted the DES models and ABM models, as can be seen in Table 2.2.

The activities of *Tawaf* have been modelled by Haghighati and Hassan [68] using the DES tool called ARENA [69]. The model is based on the system of queuing. The pilgrims were represented by discrete units, as entities of the system. After which, these pilgrims flow within the system. The utilized resources via the entities may limit the entities flow within the constructed system for the *Tawaf*. The area of Mataf and its sections were represented by the key resource that provides the pilgrims with the service. Many factors had been investigated within the model design; the behaviour of switching throughout the *Tawaf*, space availability, size of group and inter-arrival time of the pilgrim. The obtained outcomes of the simulation proposed that the switching



DES models	ABS models
Process oriented (top down modelling approach); focus is on modelling the system in detail, not the entities	Individual based (bottom up modelling approach); focus is on modelling the entities and interactions between them
Top down modelling approach	Bottom up modelling approach
One thread of control (centralised)	Each agent has its own thread of control (decentralised)
Passive entities, i.e. something is done to the entities while they move trough the system; intelligence (e.g. decision making) is modelled as part in the system	Active entities, i.e. the entities themselves can take on the initiative to do something; intelligence is represented within each individual entity
Queues are a key element	No concept of queues
Flow of entities through a system; macro behaviour is modelled	No concept of flows; macro behaviour is not modelled, it emerges from the micro decisions of the individual agents
Input distributions are often based on collect/measured (objective) data	Input distributions are often based on theories or subjective data

Figure 2.2: Comparison between DES and ABM model's attributes [67]

of lanes throughout the *Tawaf* was the most important factor within the development of crowd density, as well as decreasing the lining up system efficiency. There are other tools built depend on Discrete Event such as OMNeT++ [66].

2.3.1.4 Space-Based Modelling

Many models have used the space colonization to model agent behaviours, as in de Lima Bicho et al. [70], who presented a way of simulating the crowd. This method was based on the space-colonization algorithm. This suggested algorithm was first used to model leaf venation patterns and tree-branching architecture. In order to adapt with the modelling of the crowd, the algorithm of space-colonization focused on the spatial competition that extended between the agents during their movement. Actual crowds involved many behaviours, such as lane-formations, where the agents pursue each other, as well as relationships between an agent's speed, the density of the crowd, and collision prevention. The main contribution of this method is that the agents were capable of observing the space, capturing the signs within the agent's close cognitive field, and adjusting their behaviours accordingly. This was achieved by representing the space with various significant points.

The suggested crowd modelling method was free-of-collision where free space observing, was the main innovation of this method. Many significant points were used to represent the space which, facilitated the space competition implementation. The agents capture the signs that were located in their close cognitive field.

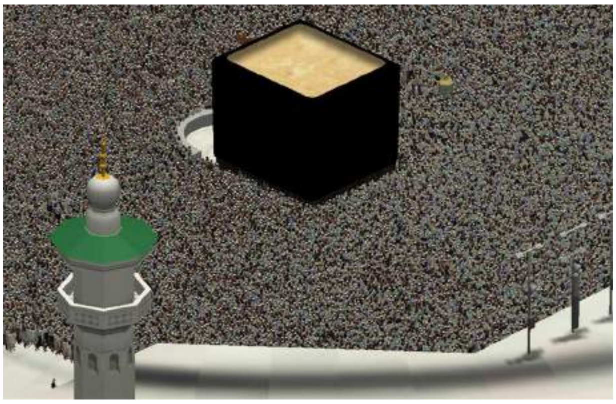


Figure 2.3: A screen shot of the *Tawaf* simulation shows the ability of the approach proposed in Kim et al. [71] to simulate dense crowds.

GPS-based modelling helps reveal real-world patterns that can inform future enhancements to the urban and architectural environment. Koshak and Fouda [43] used the Geographic Information Systems (GIS) and Global Positioning Systems (GPS) to analyse the movement of pedestrians, during the performance of *Tawaf*. Many devices with GPS capabilities were utilized to gather the coordinates of pedestrian movements during certain intervals of time. Tracking analysis computer software was utilized to analyse and visualize pilgrim movement patterns within the *Tawaf*. This enabled the users to show the interim data that could later be prepared for historical analysis. This type of analysis can play an effective role in enhancing the design of both the urban and architectural environments of the *Tawaf* area. This study had also demonstrated, that there were a number of obstacles that required elimination in order to make the movement of pedestrians easy within the *Tawaf* area. For example, the starting line of *Tawaf* was one of these obstacles that delayed pedestrian movement. The obtained results demonstrated the flow rates and service levels throughout various Mataf times and zones. The findings of the study also demonstrated the most significant times and zones for the ritual of *Tawaf*. The pilgrims track pattern movement had been demonstrated at various positions within the area of *Tawaf*. Koshak and Fouda [43] recommended eliminating the obstacles in order to make pedestrian movement easy. This proposed approach could be used within the urban and architectural design modifications of space to enhance the movement of pedestrian within the open spaces.

2.3.1.5 State-Based Simulation

State-based simulation is a technique for modelling systems by describing the system behaviours by a set of states and transitions between them. The graphical representation is mostly used to describe system behaviour. It is widely used in the field of modelling and simulating social crowds. Kim et al. Kim et al. [71] suggest the state-based approach that simulates complicated model performances, including cultural and social rules. Finite-state machines were used to determine a sequence of performances and to show the performance of this approach in various complicated situations. Sakellariou et al. [2] adopted an approach to develop an abstract generic state-based model of crowd behaviour, as based on X-machines—a type of extended finite state machine used in this thesis.

Sung et al. [72] proposed a framework to synthesize realistic crowds within complicated environments. An approach based on the situation had been used within a high-level (includes less information) case to monitor local crowd performances. However, within a low-level (includes more details) case a scheme of probability that forms the impact of many behaviours, had been adopted to drive a synthesis system with realistic motion. The results proved that this proposed framework had the ability to create complicated crowd behaviours using the behaviours and situations composition. This approach can be enhanced by adding experiments to address the situations that monitor the multi-agent statistics or crowd density. The architecture of this approach is shown in the figure 2.4.

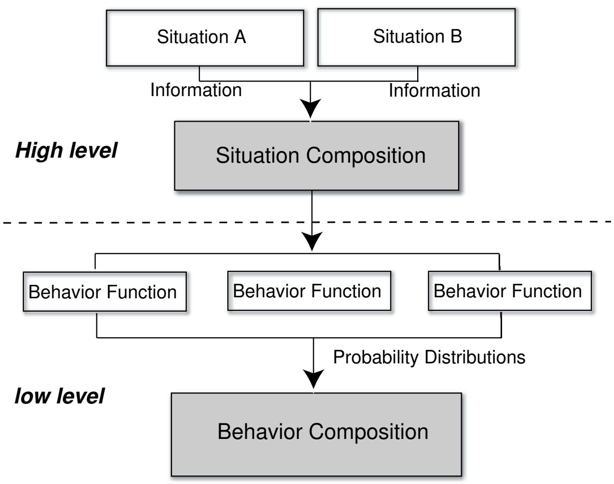


Figure 2.4: The two levels architecture approach proposed by Sung et al. [72]

2.3.1.6 Physics-Based Simulation

Physics-based simulation is recognised as an approach facilitating the creation and designing of computational frameworks centred on heterogeneous physical agents. Such an approach signifies the physical characteristics inherent in a system, namely forces and velocity, and mathematically incorporates these into the framework. This facilitates the simulation of system behaviours from a numerical standpoint [73].

A reactant algorithm had been presented by Kim et al. [71] for modelling the physics, based on the interactions within heavy crowds. The suggested approach was able to model interactions among obstacles, agents, and physical forces. Thereby, the coming collisions that occurred throughout the local movement could be avoided and identified by this suggested approach. The outer physical forces had been combined with the velocity algorithms that are based on collision-avoidance. The whole formulation generated the different force impacts that are enacted on crowds and agents, involving; the broadcasting of force throughout the crowd and the motion of balance recovery.

Elmahdy and Saleh [74] took the data associated with pedestrian speed by analysing video graphs of crossings and sidewalks, where these data had been collected at seven different locations within three Indian cities. The pedestrian crossing and walking speeds were analysed based on the facility type and gender basis. Four facility types were used to analyse the speed of walking; Carriageways, Precincts, Wide-Sidewalks and Sidewalks. In addition, the width of the road had been used to analyse the speed of crossing. The 85th, 50th and 15th speed ratio and percentile for various conditions and locations had been compared and found as terms of quantitative analysis. Moreover, the crossing and walking speed was modelled using a distribution function with continuous types for different kinds of facilities. The performed analysis demonstrated that the speed of pedestrians was dissimilar for various facilities, gender and locations. The F-test suggested that the pedestrian speed of walking was varied from the speed of crossing. Also, the results demonstrated that the speed of a pedestrian on precinct was varied from the speed on the other kinds of facilities. However, a pedestrian's speed of walking followed the standard distribution of the overall facilities and locations of the site.

Zainuddin et al. [75] discussed the *Tawaf* problem in which, the congestion within the entrances of the *Tawaf* region is presented in-particularly throughout the Hajj season. SimWalk was used to simulate the proposed model that is dependent upon the Social

Force model, and was used to simulate and model the movement within the *Tawaf* area. This lead to the first discussion in relation to the bi-directional and uni-directional movement impact, on the *Tawaf* area entrances. After which, all gates were divided into exit gates or entrance gates. The distance impact of gates on the starting position and *Tawaf* duration in this area had been studied and the various barrier designs, their locations at the exit gates, and their impact on the time that is required to exit pilgrims from the *Tawaf* area had been discussed. Hence, the pilgrims could then be equally distributed at the various entrances in order to minimize the occurred congestion at these entrances. The figure 2.5 shows the *Tawaf* region entrances.

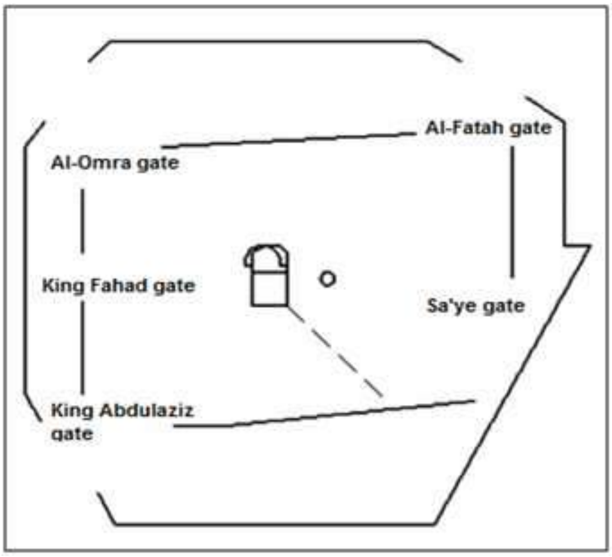


FIGURE 2.5: The entrances of Mataf courtyard Zainuddin et al. [76]

Pedestrian transition among the various models can be achieved at certain points of entry. The present hybrid approaches can be applied to join a certain model set, however they are unable to change the joined models.

Biedermann et al. [77] proposed the TransiTUM approach to overcome the limitations of the present approaches. The combination of microscopic and mesoscopic scales had been presented in this study. The TransiTUM approach had two main features that distinguish it from the present approaches; the independence of this approach from the combined models, where it can be used within any mesoscopic and microscopic models pair.

Cherif and Chighoub [78] suggested a microscopic model to simulate the movement of the crowd within dynamic environments with a high population density. The semantic side and topographic view point had been used to describe the simulation environment.

Thus, two environments with known representation approaches had been used; topological graph and grid graph. Within this work, many socio-psychological rules had been introduced that can impact on crowd performance. In addition, these rules had been combined with a social force and rule-based approach to make the simulations actual.

2.3.1.7 Cellular Automata

According to Dijkstra et al. [79], Cellular Automata (CA) can be considered as an artificial intelligence approach that simulate physical systems using mathematical modelling. Thereby, a regular rule set had been used to drive the system performance. The particular cell state can be computed by these rules, as a function to represent the adjoining cell's states and the prior state of this cell. The models of CA prevented the contact among the agents, where the space of the floor was separated as well as individuals had the ability to move into an adjoining free cell. Realistic outcomes were provided when this approach was applied in low density crowds. However, the use of this approach with high density crowds provided unrealistic outcomes.

According to Macal and North [60], von Neumann suggested a CA that was considered a discrete dynamic system, composed of a uniform grid of cells. The CA had been developed using separated time steps based on the variable value in a single cell, and is identified by the variables value in the adjoining cells. The cell's variables can be updated at the same time reliant on the variable's values within their adjoining cells as a prior step of time, and based on the local rules set. Currently, CA is successfully used within different complicated systems involving biological fields and traffic models. During the previous decade, models of CA had been used to describe the dynamics of pedestrians throughout evacuations. These models split the space into a regular grid.

The work of Zainuddin et al. [76] formed a certain extension to the pedestrian model of floor-field CA. This model was able to simulate the situations within high-density crowds that involved negative interactions between pedestrians, without bearing on the conventional discrete approaches restrictions. Two other models were involved within this work. The first one was characterized as a single environment finer discretisation, while the second enabled the overlapping of transient pedestrians within the high-density situations. These models were experimented and described within the real world and also within experimental situations. The extension to overlapping generated interesting outcomes within all situations, where the computational overheads were very low. However, the extension to finer graining was not able to enhance the basic approach, where the cost of computation was very high. This approach can be enhanced using two extensions; adding a contribution to the level of operation in order to reflect the effect of the groups presence within the simulated pedestrians, and by studying the strategic and tactical levels within larger situations.

2.3.1.8 Combined Models

Some research combined more than one simulation modelling technique to overcome its drawbacks by combining other method.Shuaibu et al. [80] presented a microscopic movement pattern of crowd simulation by , which can be applied on the pedestrians performing *Tawaf*. The suggested approach includes helical patterns for the outward and inward movements of pedestrians throughout the ritual of *Tawaf*. Three key microscopic models based on the crowd movements had been compared. These models were; model based on rule, model of cellular automata, and model of social force. Different drawbacks and advantages of these models were addressed. The suggested approach for the movement within the *Tawaf* was aimed to minimize the level of congestion in the region of *Mataf*, and the throughput of pedestrians. Average density, average time of completion and average velocity were also calculated for helical patterns of the movement. The obtained outcomes of the simulation demonstrated that the spiral suggested design path of *Tawaf* was performed better than other studied models. Curtis et al. [81] proposed a system to simulate this movement. In this system, a finite-state machine with high-level had been combined with a low-level model of pedestrians. By using this combination different behaviours had been modelled like; pausing to do Istilam (touching or kissing the Black Stone considered sacred by Muslims), exiting and entering the floor of *Mataf*, lining up to reach the Black Stone, and circling around the *Kaabah*. A model of velocity-space based on the pedestrians had been used. This model was able to display reliable results even in the presence of excessive density. The authors explained how to expand this model in order to capture the inter-agent responses of an asymmetric type. This suggested model produced positive results with and without the presence of excessive densities. The results of the simulations were compared with actual pilgrims performing the *Tawaf* ritual. This system could be used to model various behaviours, genders, and ages of the pilgrims. Figure 2.6 illustrates the structure of the combination between a finite-state machine and the model of pedestrians.

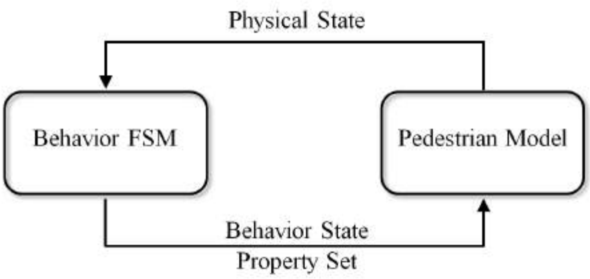


FIGURE 2.6: The structure of the combination between finite-state machine and the pedestrian models used by Curtis et al. [81]

Sarmady and Sarmady [14] presented a simple multi-layer model to process the movement of pedestrians. The individual pedestrian's actions had been simulated using a model of behaviour. On the other hand, the small-scale movements of pedestrians had been simulated using the CA model. Furthermore, a standard platform had been presented within this study to implement the suggested model. This platform was utilized to simulate various sections of the Muslim Holy Mosque. The suggested multi-agent system had the ability to simulate the impacts of the crowd that appeared within the *Tawaf* area. This work can be enhanced by improving the model of pedestrian behaviour in order to generate more accurate simulations for pilgrim behaviour within the Muslim Holy Mosque.

2.3.1.9 Evaluation and Comparison

In this section, the methods and approaches proposed in the previous sections have been evaluated and compared in order to show their validity and accuracy, and to ensure the suitability of these methods to be applied during Hajj and Umrah seasons.

In Curtis et al. [81] the suggested model produced positive results with and without the presence of excessive densities. The outcomes of many simulations were compared with the actual pilgrims performing the *Tawaf*. This system could be used to model various behaviours, genders and ages of the pilgrims. However, this system had many limitations as many *Tawaf* aspects had not been captured by this system, and the model simulates the agents individually but not in groups. Moreover, although the results demonstrated that the pedestrians should decrease their speeds however, these simulation results are not validated. The experiments showed that the *Mataf* area should be changed to enhance pedestrian movement. These results need to be validated using the data gathered from cameras and synchronized GPS devices.

The obtained results in Khan and McLeod [82] proved that the used model was able to effectively simulate and model the performance of the crowd. This work provided many recommendations and insights for the management of crowd behaviour and performance in addition to the facility layout with regards to health, safety, satisfaction, and throughput. This work can be enhanced by using an appropriate crowd simulator that is able to model the whole experiment, behaviour metrics, and features of the system.

According to Mulyana and Gunawan [15], agents in general are able to visualize the basic behaviours as experienced within the Hajj ritual. A natural behaviour of crowds can be provided by the intelligent agents. The performed simulation of a Hajj crowd in Mulyana and Gunawan [15] was able to show the performance of pilgrims in a acceptable way for training purposes within the Jamarat, Sa'yee and *Tawaf* activities. Furthermore, pilgrims can train on the Hajj activities suggested by this system before actually performing the Hajj. However, this system has many restrictions related to the number of agents that could be used within the simulation. A quantization with a virtual environment, a kinetic structure of data and better detection of collision can be applied to enhance the performance of this suggested system.

The ARENA system in conjunction with the queuing aspect had been used in Haghighati and Hassan [68] to model the *Tawaf* activities. Many factors had been investigated within the model design; the behaviour of switching lanes throughout the *Tawaf*, space availability, group size and inter-arrival times of pilgrims. The obtained simulation results proposed that, switching lanes throughout the *Tawaf* was the most important factor within the development of crowd density and decreased the efficiency of the lining up system. This proposed model can be applied to investigate more complicated crowd movements in different fields. This study also revealed that using various routes in *Tawaf* along with scheduling the entrances into the *Tawaf* area will prevent congestion during the *Tawaf* ritual, and enhance the controlling of crowd density producing a better *Tawaf* experience.

The suggested model in Kim et al. [71] was based on pilgrims' velocity information. This model was effectively operated and helped to reduce the amount of collisions among pedestrians. The results demonstrated that the suggested formulation based on the velocity was able to simulate a large number of agents (a few thousand) in a reliable manner within dense situations. This approach is efficient and could utilize large steps of time.

The approach suggested in Zainuddin et al. [75] is based on separating the gates of the *Mataf* region into entrance and exit gates. This approach enhanced the movement of pilgrims and reduced the amount of collisions. However, the implemented software within this work had many restrictions that limited the performance of the approach. This approach had insufficient computational capabilities needed to simulate large numbers of pilgrims. The reliability of the obtained results was lower than the realistic cases studied in the paper.

The approach suggested in Shuaibu et al. [80] has many constraints and limitations. The first limitation is related to the used software, where the computation capabilities are enough to perform the simulation of a large number of pedestrians. The suggested helical pattern of movements in this study can only be applied to the ritual of *Tawaf*. Generally, when most of the pedestrians follow the helical pattern, it eases the flow of agent's.

The model suggested in Sakellariou et al. [2] demonstrated the performance of the pilgrimage within the overcrowded regions. The model was able to simulate the behaviour of people with disabilities which were not simulated before. Moreover, the model was built and calibrated with real data extracted from the video clips of the CCTV cameras. The NetLogo framework had been selected to perform the simulation of the model.

According to the validation of the results presented in de Lima Bicho et al. [70], the estimation of the crowd models simulation is still difficult, especially in comparison to the results achieved in real-life (actual). The speed decay within the crowd density attained by the virtual agents within the suggested model, was consistent with the data that was measured in real life. This model can be enhanced by including groups of agents. Agents with finite-area can be used to compile a more accurate estimation for the suggested algorithm of the simulation.

The approach suggested in Narain et al. [83] was able to effectively overcome large-scale crowds by keeping the time of computation the same. However, the projection of pressure in this approach only focused on the local information, and is incapable of predicting the future collisions that can be generated from remote agents. The progress of the pedestrians was only measured for the required direction, while the human crowds within the real-life move in various directions. To solve these limitations, other techniques can be integrated with this approach to make it able to simulate massive dense crowds moving in different directions.

According to Zainuddin et al. [75], using SimWalk was an appropriate method to simulate the behaviour of pilgrims during the *Tawaf*. The obtained results demonstrated that constructing the helical path was very effective to ensure a safe, comfortable, and smooth flow of pilgrims throughout the *Tawaf*. Other methods had been suggested, such as constructing a bridge to join the *Tawaf* region with the mosque's exits. However, this approach had not studied the uneven use of the doors and the bottlenecks that occurred at the *Mataf* area entrances and they left these issues to be addressed in a future work. A summary of findings and a comparison of these studies is presented in Table 2.1.

Table 2.1: Summary of Findings

Study	Techniques	Model	Focus	Notes
Narain et al. [84]	CFD	Unilateral incompressibility Constraint; Lagrangian and Eulerian methods	*Tawaf* and other densely crowded areas	Dual-representation, discrete agents overlaid on continuous high-level dynamics. Excellent performance, handles several hundred thousand agents easily.
Zainuddin et al. [85, 86]	ABS	Social-Force Model (SimWalk)	*Tawaf*	Uses SimWalk and the Social Force Model, shows that construction of a spiral pathway can significantly increase throughput for *Tawaf*. Neglects crowd congestion at entrances.
Mulyana and Gunawan [87]	ABS	Agent based	*Tawaf*, *Sa'yee*, *Jamarat*	Models pilgrims as intelligent agents, and can be used to help train pilgrims prior to arrival. Computationally intensive, relatively few agents.
Curtis et al. [11]	ABS	FSM, RVO	*Tawaf*	Finite state machine model of crowd dynamics, pilgrims modelled as agents. Behaves well with excessive densities. Simulates 7 key behaviours. Can be extended to include more complex agents.
de Lima Bicho et al. [88]	ABS	FSM, RVO	*Tawaf*	Uses ideas from biology. Agents compete for space. Generates properties that are taken as starting points by other studies.
Khan and McLeod [89]	ABS, CA	micro-level Behavioural algorithm	*Tawaf*	Considers three parameters (courtyard layout, crowd properties, management preferences) and their effect on safety, health, satisfaction and throughput.
Zainuddin and Aik [90]	CA	Response Surface Methodology (RSM)	*Tawaf*	Extends earlier work by including congestion. Based on Response Surface Methodology. Computationally expensive, but produces excellent results.
Shuaibu et al. [91]	Mixed Models	Social-Force model, Rule-Based model, Cellular-Automata	*Tawaf*	Shows that spiral motion is more efficient than undirected circular motion during *Tawaf*, but assumes all motion occurs in a 2-dimensional plane.
Haghighati and Hassan [12]	ABS	Discrete-event system	*Tawaf*	Shows the significance of lane-switching on crowd throughput.
Sakellariou et al. [92]	ABS	X-Machines, NetLogo	*Sa'yee*	Develops a generic abstract approach and applies it to *Sa'yee*. Uses *X*-machines and NetLogo. Could benefit from translation to FLAME GPU.
Kim et al. [93]	ABS	Velocity Based And FSM	*Tawaf*	Uses ideas from physics. Allows simulation of a few thousand agents.

Key: ABS = Agent-Based System; CA = Cellular Automaton; CFD = Computational Fluid Dynamics; FSM = Finite State Machine; RVO = Reciprocal Velocity Obstacles

2.3.1.10 Lessons Learned

From the evaluation in Section 2.3.1.9 , all suggested methods and approaches, it can be seen that all studies were aimed at simulating the conduction of pilgrims during the performance of the Hajj and Umrah rituals, especially the *Tawaf* and *Sa'yee* rituals. These studies were also aimed at addressing the obstacles and limitations that restricted the flow of pilgrims, and are based on different ways of achieving such aims. Some of these studies were based on the use of the velocity information of pilgrims, whereas others were based on a software environment. Different algorithms and computational models were used to achieve the same purpose. These studies were able to fulfil these aims, albeit with some limitations. Some such works, in contrast, were unable to simulate and model large groups of pilgrims. The validation and testing of many obtained results were lower than expected or were not validated at all.

2.3.2 Commercial Tools of Crowd Simulation

In this section, we present some of the commercial tools used in previous research for the purposes of modelling and simulating crowds. Many packages and tools were found throughout the course of the search carried out. The filtered list was built depending on certain criteria:

- The ability to simulate large scale crowd (more than 1,000 agents population size),
- The inclusion of a visualisation function, either 2D or 3D,
- Past use on any published work to simulate crowd dynamics.

2.3.2.1 SimWalk

SimWalk [25] is a 3D simulation tool developed to simulate pedestrians movement. Using SimWalk, a user can define the density of a crowd, destination and the range of speed of pedestrians, etc. The movements of the pedestrians in a crowd can be simulated as well as their walking areas can be designed, by this software. Some of the other attributes of a pedestrian that can be simulated using SimWalk are: flow rates; walking speed; duration taken by each pedestrian to complete the simulation; the distance travelled; and start and exit times. This software has been used to simulate the *Kaabah* circumambulation [75] shown in Figure 2.7.

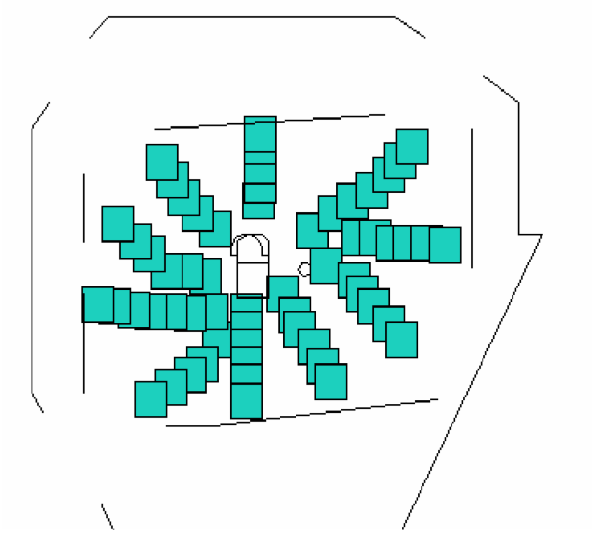


FIGURE 2.7: A screen shot of the SimWalk simulation tool shows the plotting of the waiting points in *Tawaf*, [25].

2.3.2.2 Legion

Legion [26] is a high level 3D simulation tool designed to reduce or eliminate the associated risks in crowd dynamics, and improve safety in relation to levels of congestion at high crowded density areas. It is a useful tool that offers one of the most realistic visualisations for the required environment [94]. A screen shot of the Legion simulation visualisation capabilities is shown in Figure 2.8. It should be noted that Legion was not designed as a crowd behavioural analysis system but an investigation tool for the study of large scale interactive systems. The model ignores many essential social behaviours such as assembling and leader influence. However, the concept is appealing as it appears to envision that crowd behaviour is a collection of individuals. Legion simulation system has been used in different field studies to model and study crowd dynamics [55].

2.3.2.3 PedSim

PedSim [27] is a microscopic simulation tool used at various times in underground subway terminals (and can also be used for other terminals, such as airport terminals). It helps evaluate the flow and design attributes which enables a substantial description of the

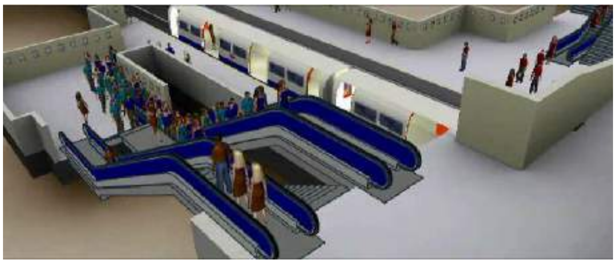


FIGURE 2.8: A screen shot of the Legion simulation tool shows a 3D visualisation, [26].

terminal, the specification of flow of the pedestrians, the identification of the design variables and the investigation of the simulation outcome. PedSim provides a certain degree of automation and gives a user the capability to indicate both the terminal design and pedestrian routes. This allows a user to develop the overall model based on these specifications. The source code of PedSim is written in pure C++ without any additional packages, and therefore can run virtually on every operating system with a C++ compiler. PedSim also provides a library that can be used in other simulation software. A PedSim simulation system has been used in [95] to simulate the social interactions for robotic navigation in crowds [96] as shown in figure 2.9.

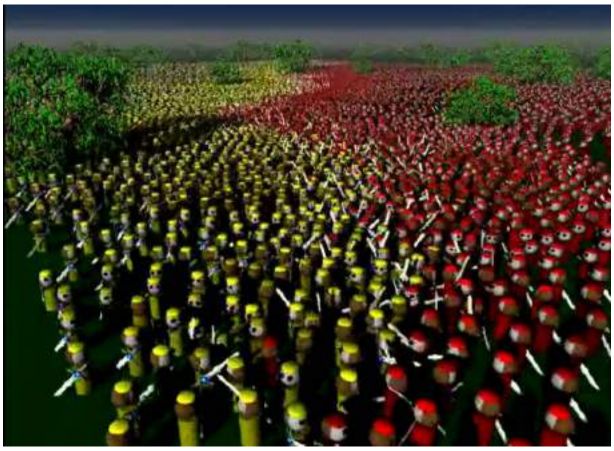


FIGURE 2.9: A screen shot of the PedSim simulation tool shows a simulation of confluence between two armies, [27].

2.3.2.4 Massive

Massive [97] is a 3D simulation tool developed originally for T.V. and filming production purposes. It provides a synthetic vision to the crowd members; however, controlling crowd members' movement requires input from the user. Due to the computational complexity of the synthetic vision technique, such a system can only be used to simulate smaller sized crowds [98–100], and is mainly focused on the pedestrians visualisation aspects rather than the behavioural aspects. A screen shot of the Massive simulation tool is shown in Figure 2.10.

FIGURE 2.10: A screen shot of the Massive simulation tool shows a simulation army in a film, [97].

2.3.3 Agent-based Simulation Platforms

There are good summaries in the literature which compare and contrast the various ABM tools [101, 102]. The *framework and library* paradigm that is commonly used by most of the ABM platforms, provides a framework and a set of standard approaches for designing and describing ABMs. This also includes a library of software that implements the framework and provides simulation tools.

Several ABM tools have emerged, each with its own capabilities, advantages, and disadvantages. This leads to sometimes conflicting use of certain aspects of the ABM by different groups of users. An example of this are the social scientists. They are less literate in programming and hence are looking for a platform that is easy to use, does not require a lot of programming, and has an easy to use interface to manage simulations. They are also not concerned about the intellectual property of the platform, i.e. whether it is open source or not. However, the type of license that regulates the toolkit is a considerable consideration for computer scientists; they want the ability to meddle with the toolkit at a lower level and to have programming flexibility in order to modify or extend the software as necessary with third party applications. The built-in interfaces, are usually less computationally efficient, therefore computer scientists do not use them and generally prefer to program simulations themselves in order to save execution time. Educators of ABM prefer pedagogical packages that are easy to learn, and provide the student with the necessary competence and skills to advance to more difficult and extensive toolkits latter on. Moreover, the visualization capabilities vary among them. Some of them offer a text only output while others are able to produce a 2D, or 3D output [102]. In the following Sections we discuss some of the ABM tools used in previous research.

2.3.3.1 Netlogo

NetLogo [103] is a functional programming language which uses turtles (agents are called turtles in NetLogo) to represent agents, and comprising states such as unique identity, position, and user-defined attributes. The position of an agent in the space is represented by a patch (also called a cell). Each patch has a so-called patch-own variable that stores information, such as the size and visibility of the patch, etc, about the patch. This information helps compute the movement and density of the agents. (More information available on Section 3.11.7).

2.3.3.2 Swarm

Originally, Swarm was created at the Santa Fe Institute [104] , with developments since being made by the Swarm Development Group. The underlying structure of Swarm is the simulation of various groups of agents interacting simultaneously, with this model developed into the coding and agent inspector actions incorporated as part of the agent group. Accordingly, in an attempt to visualize one agent, non-interacting hidden agents must be used [105]. Swarm is recognised as being a stable platform, and is most adequate in relation to hierarchical models. When considering structure formation good mechanisms are delivered through the adoption of multi-level feedback, which is facilitated between the environment and agents or groups of agent. Networking agents are not offered direct library support, nor is there direct support for adaptation mechanisms. Writing of networked causality is simplified to some degree when Swarm is programmed in ObjectiveC because of its message-passing approach. However, programming Swarm in ObjectiveC requires learning the language, which may be problematic for inexperienced programmers. Various statistical measures are provided by SWARM. Swarm's documentation is not complete and outdated. However, the current documentation provides enough information [105] to use Swarm in various studies. Swarm can also be programmed in Java, but due to the lack of documentation and code examples it is more challenging than programming in ObjectiveC. In either case the utilisation of Swarm requires advanced programming skills.

2.3.3.3 Repast

Repast (REcursive Porous Agent Simulation Toolkit) is a platform that is known to be well-developed and widely utilised, and incorporates a number of advanced features. Initially, it was introduced as a Java implementation of the Swarm toolkit; however, significant developments saw it expand to deliver a comprehensive toolkit for ABMs [105]. Essentially, Repast is known to be easy to develop into complex and large-scale models, and delivers a number of useful tools and facilities, including displays (both 3D and 2D), charting models, statistical packages and logging results. The present Repast includes the Colt Java libraries for statistics, whilst newer Repast Symphony includes the R statistical suite. One of the most valuable aspects of the Repast library can be seen in its approaches to reading input parameters, with batch runs and two-format support recognised in consideration to its special features. A component centred on establishing neural networks is also offered by Repast, which is known to be valuable in applying agent learning [105]. Overall, documentation may be described as good, as is the user community; however, a greater degree of technicality is involved owing to the more progressive and sophisticated features delivered by Java.

2.3.3.4 MASON

MASON (Multi-agent Simulator of Neighbourhoods) is a general purpose ABM library, tailored to achieve higher speeds, and large batch runs of simulations [106]. MASON is Java-based, as is Repast, and delivers a number of the same characteristics as Repast, but is known to be deficient in some of the more fundamental features. This was a purposeful design choice owing to the fact that the role could more than adequately be filled by a pre-existing library. Principally, the benefit of MASON can be seen in its speed; nevertheless, its speed is only slightly faster than that of Repast, and may even be slower than some models of Repast, as can be seen by the work of Railsback et al. [107] . One other benefit of MASON is related to batch runs, where simulation may be prevented on one machine but replicated and reinitiated on another. Most significantly, some of the batch parameter file format support provided by Repast is lacking in MASON and there are also various other difficulties when establishing a graphical user interface (GUI) display, and corresponding display agents; this needs to be carried out in a complex and cutting-edge fashion. In addition, the drawing of icons may be problematic for agents on screen, although the good inspection of agents' states, on screen, is achieved. With all of this taken into account, it is suggested that MASON should be adopted where sophisticated batch runs and speed are necessary. MASON is a sound choice for the exploration and analysis of adaptation, in addition to networked causality [105] .

2.3.3.5 FLAME

Flexible Large-scale Agent Modelling Environment (FLAME), which was originally devised by Coakley [108] at the University of Sheffield [108], is concerned with providing an agent-based project on the simulation of biological cells developed within different environmental conditions. One key objective of the project was concerned with writing the requirements for a formal model, facilitating, through the use of modellers, the simple creation, exchange, inclusion and coupling of models written in high-level modelling language [109]. The distribution of agents over many processors, the development of parallelisation approaches and the inclusion of testing approaches in order to verify developed models were the main aims of the development. FLAME is founded on the commonly referred to finite-state machines; in other words, automata specified by a finite number of states, transitions between those states, and actions commonly utilised in computational sciences [110]. The methodology implemented through FLAME is to consider all agents as X-Machines, and to accordingly outline a communication structure through which the various agents are able to communicate with one another. Importantly, the framework has been modified and improved by Coakley [108] in order to facilitate its running on a corresponding computing platform. In the past, the model was utilised in order to examine biological systems' behaviours at various levels, namely cellular, molecular, social and tissue. Importantly, there has been much success in uncovering various biological properties that have been previously confirmed experimentally through the work of Coakley et al. [111] . The most recent version of the FLAME framework, referred to as FLAME- II, centres on FLAME and FLAMEGPU, which establishes a back-end aspect intended to function on different hardware architectures, as well as the case of high-performance machines. The new suggested architecture breaks down the simulation into a number of different vector operations, all of which with the potential to be scheduled in line with a dependency graph. This graph may be created through examining each agent function's own memory accesses. The new method will facilitate different optimisation opportunities, with the inclusion of data structures that are more effective and valuable, improved resource utilisation with the application of dynamic task scheduling, and various levels of parallelism[112].

In regards key points underpinning FLAME Allan [113] are descried as follows

- FLAME is a modelling environment allowing high performance agent based modelling on parallel architectures;
- Modellers do not require specialist knowledge of the underlying architecture used for simulation, as models are designed using formal specification techniques;
- Efficient algorithms for inter-agent communication and birth and death allocation ensure maximum simulation performance;
- The system is based on a simple XML syntax which is easily extendible;
- Performance of complex cellular tissue models has been increased drastically.

2.3.3.6 Flame GPU

FLAME GPU [114] developed at University of Sheffield is a high performance Graphics Processing Unit (GPU) extension to the FLAME framework. The FLAME GPU provides parallelism and allows the user to program agent models with the ability to scale to massive sizes, while still ensuring that the simulations run within acceptable time constraints. Current implementation supports Windows, Linux and Mac OS X operating systems. Formal agent specifications are mapped into simulation code. Agents are indicated using a communicating X-Machine concept, which is an expansion of the Finite State Machine that includes memory. There is a globally accessible message list implemented in FLAME GPU which is used by the agents to store their messages, and this enables them to communicate amongst each other. X-Machine Mark-up Language (XMML), which is XML syntax with schema governing the content and is used as a format to specify the simulation models.

A common XMML model file is comprised of a specification of a number of X-Machine agents (including memory, state information and a set of agent transition functions), a number of message types (each containing a list of globally accessible messages) and a set of simulation layers which specify the execution order of agent functions (which is

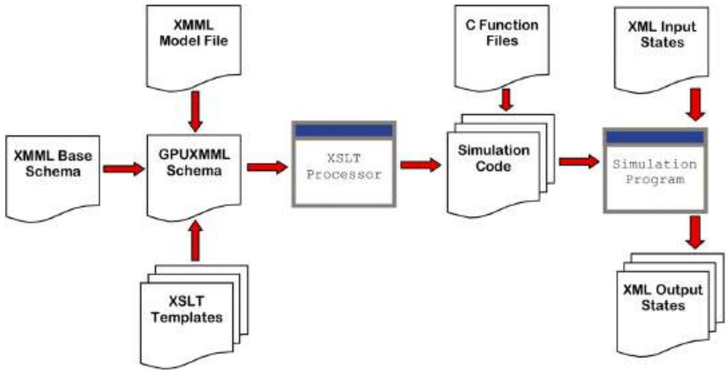


Figure 2.11: The FLAME GPU modelling process [1]. Models are translated from an XMML file using a template processor which produces simulation code.

comprised of a single simulation iteration). Figure 2.11 shows the process of generating a FLAME GPU simulation [1].

When presented with an XMML model definition file, Extensible Stylesheet Transformations (XSLT) are used to automatically generate template driven code. XSLT is a flexible functional language based on XML (and is verified and validated using a W3C specified Schema) and is appropriate for the conversion of XML documents into other file formats using various other compliant processors. The FLAME GPU SDK provides its own processor for such purposes. A number of XSLT Simulation Templates are specified, that generates a Dynamic Simulation API to link with the Agent Function Files to compile a simulation program. A user (modeller) can explicitly focus on specifying agent behaviour and run simulations without understanding any GPU programming and optimization approach.

2.4 Simulation and Modelling Crowd in the Hajj

Khan and McLeod [82] used the technique of Agent-Based Modelling and Simulation (ABMS) to investigate the effect of the courtyard layout of Al-Masjid-Al-Haram, pilgrim crowd properties and management preferences of Hajj authorities on the urgent performance of the *Tawaf* crowd with regard to safety, specifically health, satisfaction and throughput. Using this technique, the micro-level pilgrim performance had been modelled in order to simulate the emergent performance of the crowd to give better:

- Health by decreasing the contagious diseases that can spread throughout the *Tawaf*;

- Satisfaction by giving a calm environment that helps to focus on the worship;
- Throughput by handling the total number of pilgrims that may extend between two and four million;
- And safety by minimizing the number of casualties.

Mulyana and Gunawan [15] simulated the crowd of Hajj based on intelligent agent development. Intelligent agent's notion had been used to construct the performance of the crowd for the pilgrims. The outcomes proved that the simulation of Hajj crowd demonstrated the practical performance of pilgrims for three main activities of Hajj; Jamarat, Sa'yee and *Tawaf*. In addition, this proposed system could be utilized to train the pilgrims prior to performing the real activities. One of the limitations of their Intelligent agent implementation is the limited number of agents that can be simulated. This number could be increased using a superior computer processing power. However, some improvements could be performed like; applying quantization with a virtual environment, implementing a kinetic structure of data and utilizing a better detection of collision. Their general agent structure is shown in Figure 2.12.

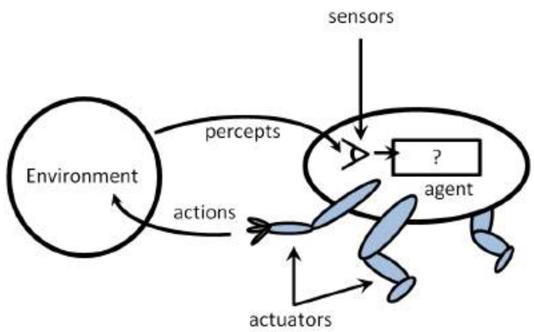


FIGURE 2.12: Intelligent agent structure, [15].

MAKKSim had been presented in this study as an agent-based tool for the simulation of pedestrian dynamics. MAKKSim software platform is developed by the Complex Systems and Artificial Intelligence Research Centre (CSAI). This software enables the end-users to visualize and simulate the dynamics of the crowd within closed and open organized spaces. Manenti et al. [115] presented a software architecture and developed a model of MAKKSim based on the agent performance definition, end-user interface and UML diagram analysis. This work can be enhanced by integrating the platform of MAKKSim with other tools for input and output simulation analysis. Moreover, one of the ongoing stages of this enhancement is the integration between. The Granulometric Distribution Tool (GDT) tool and MAKKSimin the study of pilgrim groups. GDT tool has the ability to determine the initial simulation configuration, by identifying the features of a group within a known environment. The figure 2.13 below illustrates the interface of MAKKSim.

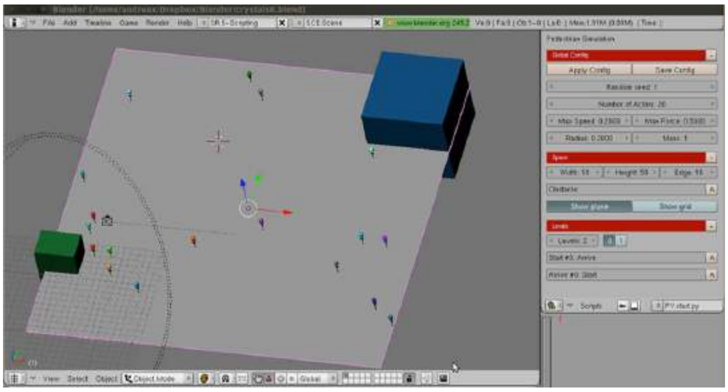


FIGURE 2.13: The interface of MAKKSim, [115]

Narain et al. [83] proposed a scalable new approach to simulate crowds of huge densities. The authors applied a dual representation involving a continuous system and discrete agents. Within the settings of a continuous system, a new contrast restraint has been introduced to simulate and model the performance of a crowd within a wide-scale.It also aimed at accelerating the avoidance of inter-agent collision within the dense situations. This suggested approach was shown as able to simulate dense crowds that consisted of many hundreds to potentially thousands of agents. The performance of this approach varied, based on scene complexity, the roadmap of global planning, and static barriers. However, the results obtained demonstrated that, when the number of agents reached one million or more, the issues of memory became a very important factor. An overview of the approach algorithm can be seen in Figure 2.14.

2.5 Simulation and Modelling *Sa'yee* Ritual

In the literature, most of the researchs carried out in the field of Multi Agent Systems in the *Makkah* area took the *Tawaf* as a case study, while few of them considered the *Sa'yee* see section 2.3.1.9. The reason for prioritizing *Tawaf* case studies, is due to the number of crowd incidents occurring during the *Tawaf*. This is because of the solo floor nature and the layout of the Mataf, which allows bottlenecks to occur; see Figure 2.15. In [15] some

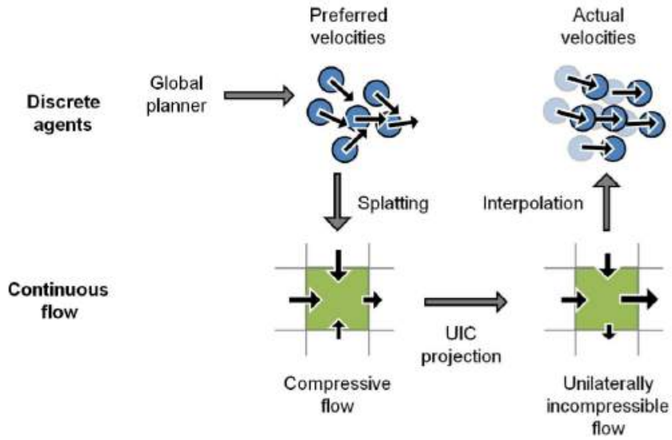


Figure 2.14: Narain et al. [83] suggested approach algorithm for dense crowd.

case studies performed simulations for Hajj activities including the *Sa'yee* ritual. Their model was able to simulate only 300 agents due to the limited processing capabilities of the hardware. This model was built for educational objectives and was unable to simulate a huge number of agents for other purposes, such as planing for emergency situations. The model simulated the *Sa'yee* ritual as a process but without including any sophisticated behaviours for agents such as grouping. In [16] a simulation model was built to evaluate the performance of pedestrian emergency evacuation processes in crowded large-scale facilities, such as the corridor in Al-Masjid Al-Haram. It was implemented in a Cellular Automata platform to capture the different behavioural rules and their impact on the performance of the evacuation process; such as choosing an exit gate, the path to it, and frequency of updating the choice of exit gate. A comprehensive model in [17] incorporates prediction and decision making capability into a Social Force Model to make the model capable of reproducing what actually occurs when a pedestrian investigates his/her walkway while a group of pedestrians are in front of him.

Ilyas [116] proposed a model for Ramy Jamarat ritual. NetLogo had been used to develop this model and to perform the simulation for this ritual based on the defined parameters of the user. These parameters involved; time required to perform Ramy, Jamarat hitting range and view range of Jamarat. Different Jamarat pillar shapes were analyzed for pilgrims queuing that occurred throughout the Ramy involving; deformed ellipse, ellipse and circle. The outcomes demonstrated that the elliptical shape performed better for pilgrims queuing than other shapes. The outcomes of this model demonstrated that it is still in the rudimentary stage, where many parameters were required to enhance its performance. This model can be improved through identifying the significant pilgrims

Figure 2.15: A Photo of Al-Masjid Al-Haram showing the rectangular shape of the Mataf that creates a bottleneck during circumambulation [38].

feelings like; directional focus, confusion, anxiety and fear which play a significant role within the crowd dynamics. The figure 2.16 illustrates the simulation overview.

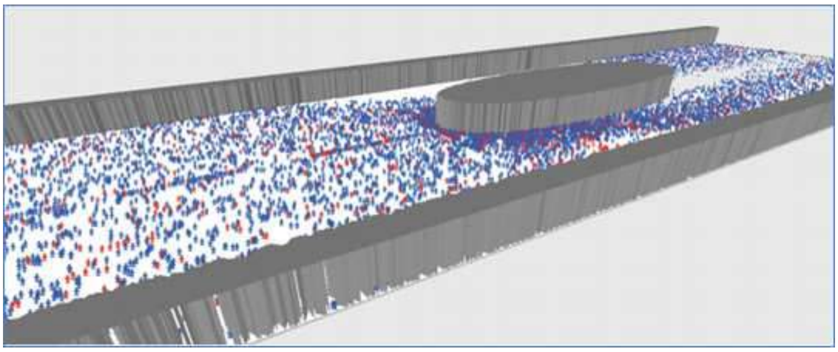


Figure 2.16: The Jamarah simulation model in NetLogo developed by Ilyas [116].

Sakellariou et al. [2] proposed an integrated and coherent approach to analyse, simulate and specify crowd performance. This involved:

- 1) A common modelling framework utilizing X-machines;
- 2) A strong and flexible agent based simulation modelling which implemented the derived model from the specification of X-machines (see Figure 2.17);

- 3) A strict method to extract the performance patterns, parameters and data from videos as well as many procedures of analysis and validation that used to simulate the outcomes.

This suggested approach had been illustrated for Hajj, which demonstrated people performance within an overcrowded region. The *Sa'yee* ritual had been selected to show the pilgrims performance. NetLogo had been used to simulate the results of the model.

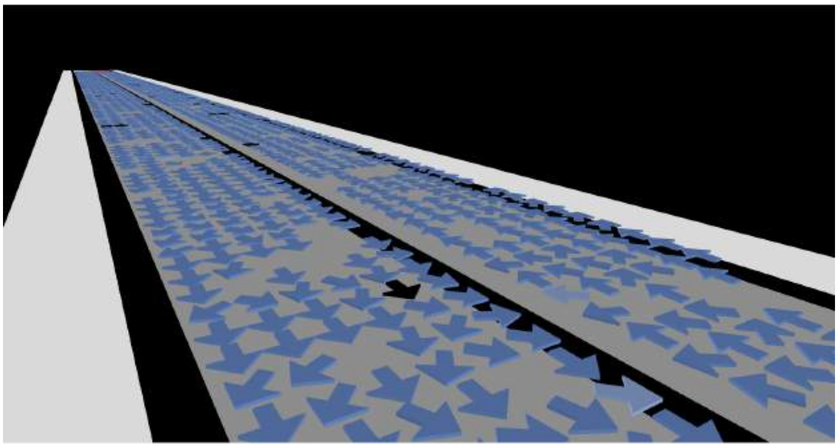


FIGURE 2.17: A screen shot of Sakellariou et al. [2] *Say'ee* model

Chapter 3

Materials and Methods

3.1 Introduction

Social crowd modelling and simulation is a significant topic, and much research has been done to simulate social dynamics; however, all of them have been used experiments within lab settings to extract models parameters. It is very important to feed your model with accurate parameters in order to achieve reliable results. Because of this, the decision was made to build our simulation model on actual data. This decision cost considerable time and effort in identifying a case study suitable for applying our research. One of our criteria was the availability of CCTV facility and permission to access it. One of the challenges was seen in how crowd parameters could be extracted from the videos taken by unknown camera sittings and position. To deal with this challenge, we creates a novel and rigorous method of extracting data, parameters and patterns of behaviour from videos; we then proposed a flexible and robust framework based on X-machines. Moreover, we implanted agent-based simulation environments derived from the X-machine specification on the Netlogo [103] simulation platform. Finally, we escalated our model and implemented FLAME[117] to afford the model the capability to simulate a large-scale crowd. In this chapter, we covered all tools used and methods applied on the chosen cased study (*Sa'yee*) to model, implement and simulate the system. A state-based ABM was chosen due to its capability to represent the interactions between components of the complex systems.

3.2 Data collection

Within this stage, appropriate video recordings have been collected from 36 experiments were conducted in a six different locations with the objective to study the effects of different variables on the pedestrian walking speed, such as:

- Agent height by collecting data from different countries (Saudi Arabia and UK);
- Weather conditions by selecting different places(outdoor,indoor,rainy,);
- Walking style by selecting (normal individual, using umbrella, cellular phones and carrying bags);
- Age and gender by selecting (men, women, elderly men and women, kids);
- People with disabilities by selecting (normal wheelchair, motorised wheelchair, elderly scooter);
- Purpose by selecting different places type (Universities, Shopping malls, Open market and holy places);
- Groups by selecting different group styles(couple, family, group of 3).
- Surface friction such as smooth marble, Asphalt, sloping floor.

More focus has been given to *Sa'yee* rituals in *Al-Masjid Al-Haram* mosque, as it is the case study of this thesis. We got an access to a huge number of video recordings of the *Sa'yee* then we choose appropriate clips for our work. In our experiments at *Al-Masjid Al-Haram*, there is no special camera has been used to observe the behaviours of pedestrians or to capture different recordings of pedestrian behaviours. Only CCTV recordings were used in addition to special notes and lessons taken from two authors who published papers about the *Tawaf* Area simulation. These notes and lessons summarized the author's experiments; along with the difficulties they faced, and have been taken into account so that they could be avoided. Interviews have been conducted with; Dr. Basim Zafar and Dr. Nabeel Koshak, to gather information about the Al-Masjid Al-Haram area, limitations, prior researches, plans and rules. The collected information involving future plans, rules of traffic management, photos and videos, played an important role within the research done in this thesis.

All this collected data has been used to extract the characteristics of crowds. In order to make the speed measurement method valid for all of these experiments, many physical measurements have been collected for selected objects within each clip, in order to consider these measurements as a unit of scale. For this purpose, a drawing(blueprint) os *Al-Masjid Al-Haram* has been collected to take and identify the distance between the pillars, the type of van has been obtained from the photo to set up the dimensions of the van from the official website of the van factory and the actual size of the tiles that existed within Meadowhall Mall have been measured and identified to confirm the validation of the work carried out in this thesis.

In the following sections, a short description and overview provided of the experiments.

3.2.1 Experiment of Studying Crowd at *Al-Masjid Al-Haram*

These experiments have been made in *Al-Masjid Al-Haram* between 2013 and 2014 in support of CTHMIHR. The data were collected from CTHMIHR are for two rituals *Tawaf* and *Sa'yee*. These data include (Drawings and blueprints of the facility, guidelines and rules controlling crowd flow, HD videos recordings of *Tawaf* and CCTV video recordings of *Sa'yee* ritual). The data have been processed using the methodology presented in Figure 3.10. Figure 3.1 shows a screen shot of the tracking process for a group of three pedestrians while performing *Sa'yee*.

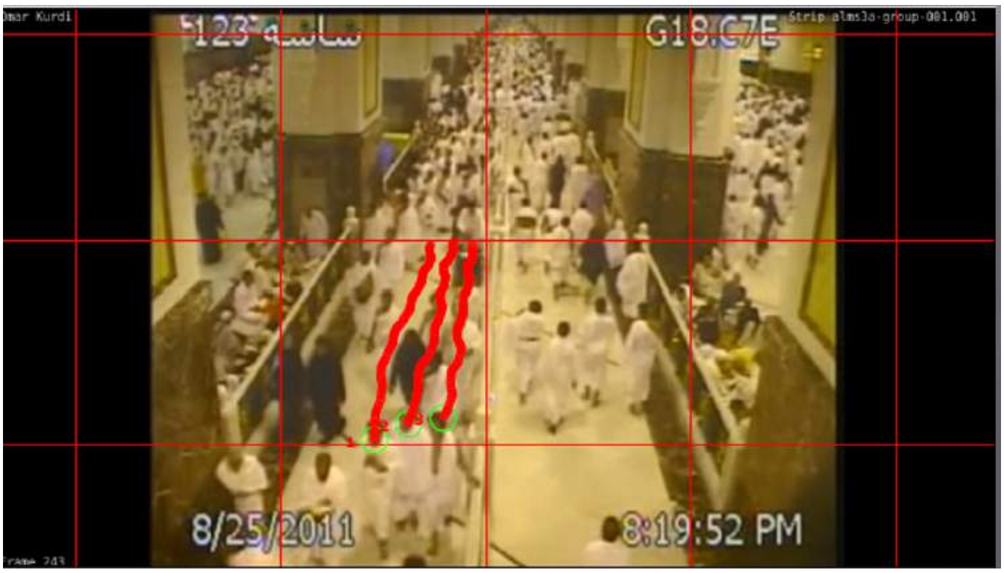


Figure 3.1: Trajectory tracking for a group of 3 pilgrims on PeTrack.

(A) Crowd behaviours and patterns extraction in the *Tawaf*

(B) Crowd behaviours and patterns (magnified version)s extraction in the *Tawaf*

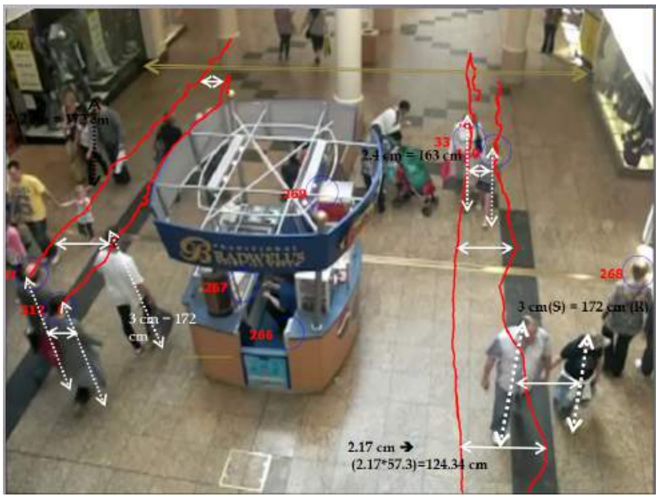
FIGURE 3.2: Crowd patterns and behaviours extraction difficulty at *Makkah* during *Tawaf* for large crowd with high density.

3.2.2 Experiment of Studying Crowd at Meadowhall Shopping Centre

Meadowhall Shopping Centre located in Sheffield is one of Britain's biggest shopping centres with 25 million annual visitors [118]. People with various interests visit the centre for different reasons. Explicit products and services help to lead and direct people to certain sections of the shopping centre; this can cause congestion issues to arise in certain sections of the mall, whereas other sections may demonstrate lower congestion issues. To improve the shopping experience of the people, Meadowhall is testing a new system in which walkways are separated into a slow and a fast lane; this is also referred to as an overtaking lane. This helps to avoid the holding up of serious shoppers by those wanting to stroll through the centre content to window shop [119]. Most people frequently visit public places, such as train stations, stadiums, parks and shopping malls. Therefore, it is very important to design efficient and safe models in such cases. Shopping centres normally contain different areas for shops, supermarkets, restaurants and departmental stores. The most important issue at a shopping centre is that the location of the shops and services are the main determining factor of where people will visit. Observing video clips or using informational data collected through customers can supply valuable knowledge and intelligence pertaining to consumer movement behaviour. Identifying possible issues and predicting the utilisation of different sections can be achieved through a computational model, which has been calibrated using the aforementioned data. In studying the crowd at Meadowhall, a series of video recordings of the crowd flow have been collected. Professor Daniela Romano offers access to these videos for research purposes. All videos have been observed extensively to extract patterns of crowds at the shopping mall. We applied the extracting characteristics methodology see Figure 3.10. Speed and density were calculated from the videos for different types of visitor (individuals man/woman, couples, family with 2 kids and disabled). The main observations of the Meadowhall crowd can be summarized as follows:

- Pedestrians walking at two sides of corridor are slower thank those in the middle, because of looking at window shops or reviewing promotions;
- Shoppers have various goals and destinations so they walking in a bi-directions which is cause collisions specially while using cellular phones for texting or calling;
- Families with kids are the slower groups as they controlling (stop and wait) their kids.
- Motorised wheelchair always matching normal able bodies speed (no overtaking has been noticed).

Figure 3.3 shows analysis and measurements of shoppers trajectories in the Meadowhall shopping centre. In order to validate the measurement and calculation we used the tile's size as a scale unit to calculate pedestrians travelled distance. In Figure 3.4 a screens shot of precessed frame after tiles edges rendered for distance calculation.



Description	Screen measurements
Corridor width	11 cm
Initial distance between pedestrian and child	0.6 cm
Initial distance between pedestrian	0.8 cm
Man height	3 cm
Woman height	2.4 cm
Maximum distance between couple	1.6 cm
Minimum distance between couple	0.7 cm
Maximum distance between adult and child	2.17 cm
Minimum distance between adult with child	0.6 cm

FIGURE 3.3: Crowd behaviours and patterns extraction from video recordings at Meadowhall.

FIGURE 3.4: Distance calculation using Meadowhall's tile dimensions.

3.2.3 Experiment of Studying Crowd at Trinity Mall

Trinity Shopping Mall is located in Leeds. It is a medium size shopping mall with over of 130 thousand visitor at the peak time [120]. People with various interests visit the centre for different reasons. A series of experiments were performed on its corridor so that new data for different location and configuration could be collected. The main characteristics of the crowd at the Trinity Mall are:

- The corridor is slopped making the speed of people going down generally higher than the speed of people going up;
- It has outdoor corridor where we can study various crowd behaviours and patterns at different weather conditions.

(A) Faster walking agent walking through the middle.

(B) Individuals walking and carriying shopping bags

FIGURE 3.5: Experiments in Trinity shopping centre to collect speed of different pedestrians types.

- Different classes of pedestrians could be considered as different people could be individuals carrying bags or Wheel Duffel Suitcase and many more (see Figure3.5b);
- The pedestrians (agents) had different goals and destinations;
- It was found that the pedestrian walking in the middle of the corridor had higher speeds compared to the pedestrian walking on the sides. The ones on the sides were more distracted by the advertisement (see Figure 3.5b).

3.2.4 Experiment of Studying Crowd at Birmingham Farmer Market

Birmingham farmer Market is an urban market located at Birmingham, U.K. The study of crowd behaviour and pattern at Birmingham farmer Market gives the effect of the use of umbrellas on the walking behaviour of pedestrian. Further the difference in the walking speed and crowd density when carrying umbrella so that no collisions occurred was also the main interest of our observation. The data were taken in the coordination with the research team of Dr. Romano. The main characteristics of the crowd are listed below:

- Most of pedestrians walk at their lower speed to watch shops windows and promotions;
- Asphalt floor provides rigid base to walk and more grip to the pedestrians;
- The outdoor setup offers various type of weather conditions affecting the crowd behaviours at different seasons and weather (see Figure 3.6a). Further the speed

(A) Extracting under different weather conditions and while people using umbrella

(B) Elderly individuals using motorised scooter

FIGURE 3.6: Experiments in Birmingham farmers market shows data extraction in a different walking style and weather condition(wet).

of motorised scooter used by the elderly people was found to be nearly equal to the speed of normal people (see Figure 3.6b);

- Various goals and destinations of visitors(agents) causing random interaction between the agents;
- People tend to increase the respect distance whenever they see others using umbrellas.

3.2.5 Experiment of Studying Crowd at University of Sheffield

This experiment was based on the video recordings provided by Dr.Romano research group and used in this thesis with her permission. The methodologies of extracting crowd characteristics have been applied on all videos and we analysed and observed crowd behaviours carefully. The videos show numerouus students passing in front of the Hicks building. These recordings were used to test and verify the calculation and the method proposed in this thesis. Each video clip was observed carefully to extract generalized crowd behaviour. We then extracted parameters, such as walking speeds within groups for the various types of persons. To determine the travelled distance of each pedestrian we measured and used a real object, such as a vehicle's (in the parking lot) dimensions as a scaling unit (see Figure 3.7). It can be seen that the people in the university are motivated by different purpose than in other places and hence they show different behaviours in terms of speed, compared to a shopping mall or an outdoor market.

The main properties of the University crowd that as follows:

- Most of pedestrians walking at their higher walking speed to catch up classes;
- Walking in-door in air conditioning corridors;
- Marble floor (even floor environment),smooth and no up/down slop;
- The purpose of walking is different here as most of pedestrians in hurry to catch up class or take a break and return.

3.2.6 Using Unmanned Aircraft Systems(UAS)

We used a consumer-graded unmanned aerial vehicle (drone) to monitor the dynamics of mass gathering in a public area. Then we extracted crowd characteristics from the aerial captured video, with attention assigned to the speed and density of people in the crowd. The benefits of using such facilitates clearly appear when monitoring crowds in large open areas. We were able to use it in one location only, which was Leeds Becket University; this was as a result of the guidelines and restrictions implemented in the use of this facility. Utilising UAS in studying and monitoring crowd behaviour has been

FIGURE 3.7: Speed extractions and calculation by using car length as known scale unit.

witnessed in many countries, such as the UK, as demonstrated by police departments [121]. In this thesis, we carried out some experiments on this technology, with the plan to use it as a primary camera in future work.

In specific consideration to this experiment, the decision was made to utilise a drone see Figure 3.8, which was considered an affordable approach without making any unnecessary compromises in terms of quality. It also satisfied all necessary specifications from a technical standpoint, i.e. camera, GPS, heavy duty-load, better flight time, etc. The drone selected encompassed a camera capable of producing 1080p HD video at 30 frames per second through the Vision app. Notably, the camera was 14 megapixels. The software and apps were recognised as compatible with both Android and iOS. Moreover, the Vision allows the camera to be tilted, meaning it can create a more seamless video. In addition, the battery included is a 5200 mAh LiPo (lithium polymer) battery; this means the drone has 25 minutes' flight time during each instance of charging. Furthermore, photographs and video may be transmitted up to a range of 300m when connected through Wi-Fi and a pre-installed GPS; this therefore offers greater control and stability in terms of hovering. One further benefit of the DJI Phantom 2 Vision can be seen when considering its compatibility with both iOS and Android operating systems. This means the drone can be linked up to any tablet or phone. Moreover, when linked through GPS, the camera installed in the drone communicates and stores the information onto the device. Furthermore, the auto-return mode means that the drone may be safely returned to the take-off point. This essentially adopts the role of safety mode when the drone is lost; the drone would then return without compromising in terms of privacy or otherwise with causing damage. This approach, however, depends on GPS availability[122].

FIGURE 3.8: DJI phantom vision 3 pro drone

3.2.6.1 Feasibility of Using Drone for Crowd Analysis

The experiment at the Leeds Becket University was conducted with the help of drone with permission form the security department of the Leeds Becket University. We maintained all the ethical standards and all regulations were followed regarding the operation of drone in open space. The experiment was conducted on Sunday such that the traffic and crowd was low. The experiment tests the feasibility of the use of such technologies in agent based modelling processes. We were able to track the people successfully after few unsuccessful trials(see Figure: 3.9a,3.9d). The failures in the attempts can be explained as the disturbance in the recording caused due to wind speeds leading to the swinging (instability) of the drone. More advanced drones should be used if we intend to have more stability and reduced swinging This will enable us to track and study the trajectory even on different weather conditions as well.

3.3 Methodology Flowchart

An overview of the crowd analysis methodology including the steps involved is given in Figure 3.10. We give detailed descriptions about each of these steps in the following sections.

(A) Tracking a woman from drone video footages successfully

(B) Fail to track Indiviuals due to drone stability

(C) Tracking a man from drone video footages successfully

(D) Fail trial to track a couple

(E) Tracking man within group of 3

FIGURE 3.9: Tracking pedestrian by using drone depends greatly on the drone type and the weather conditions.

3.4 Pedestrian Trajectories Extraction

Actual empirical data of crowd flow is essential to verify and analyse the pedestrian dynamics. The obtainable database is highly contradictory, inaccurate and small. Using

FIGURE 3.10: Methodology flow chart of extracting crowd characteristics from video clips.

the manual methods to gather this data required too much time and obtained inaccurate values of time and space. Due to this, Pedestrian Tracking (PeTrack) tool has been used to extract trajectories of pedestrians from the recorded videos in an exact and automatic way. There is also a lack of obtainable empirical data related to the variation among the behaviours of pedestrians in various countries. Thus, analysing the actual video recording taken from real situations is the most suitable way to study and observe this topic. The behaviours of pedestrians in the actual videos is natural without any modification or intervention from an external source, which makes this research more credible by using real video footage.

To perform data extraction, three different video recordings of the actual daily activities were gathered from three various locations. All video clips were carefully observed to extract the required behaviours like; a disabled individual walking(electric wheelchair), pedestrian groups, young as well as elderly men or women, in short views. Afterwards these views were trimmed to 10 second recordings that only represent a single case. These reduced recordings can be utilized by any video editor. The new clips were then saved within a single folder to be reduced into a sequence of photos. These photos were then stamped with an assigned file name and sequence number. The trajectories of the group and pedestrians were extracted from the sequenced photos via the PeTrack Software. Thus, any tool of screen measurement can be utilized to analyse and identify the pedestrians height at each trajectory's beginning or end, to compute the required characteristics and speed. The final procedure is to include all pedestrian types from all views, and compare them with each other in order to identify the crowd specifications. These steps are summarized in the section 3.3.

The validation process is very necessary to validate the obtained results from the extraction procedure. In this work the results have been validated as follows:

- Ten clips of video were taken from two various positions using a camera with an unknown angle;
- The outcomes of the suggested method were compared with the real measurements of the object;
- The real dimensions were measured using the scaling technique, which searches the objects with known dimensions and size in photos and then utilize this technique as a scale to find and measure the unknown dimensions of other objects.

For further explanation, the actual size of the tile that was presented in Meadowhall Mall was identified and measured to be utilized as a unit of scale in order to compare the pedestrians' speed obtained from the recorded videos of Meadowhall. Furthermore, the extended distance between two columns were measured and used as a unit of scale to compare the pedestrians' speed in the *Sa'yee* corridor.

3.5 Speed Calculation

We use the following equation to measure the speed of an agent (AS).

$$AS = \frac{DT}{TD} \tag{3.1}$$

where, DT = distance travelled and TD = time to travel the distance, and are computed as follows.

DT is computed using Meazure [123]. We first select a specific area from the corridor (environment) with known length, and a pedestrian to be tracked in this area. We then extract the selected pedestrian trajectory from the beginning to the end of the selected area. The difference in height of the selected pedestrian, shown as a in Figure 3.11, is measured at the beginning (position 1) and end (position 2) of the trajectory. The euclidean distance (also DT), shown as c in Figure 3.11, is measured from position 1 to position 2. A visual representation of measurement of DT is shown in Figure 3.11.

$$TD = \frac{NF}{FPS} \tag{3.2}$$

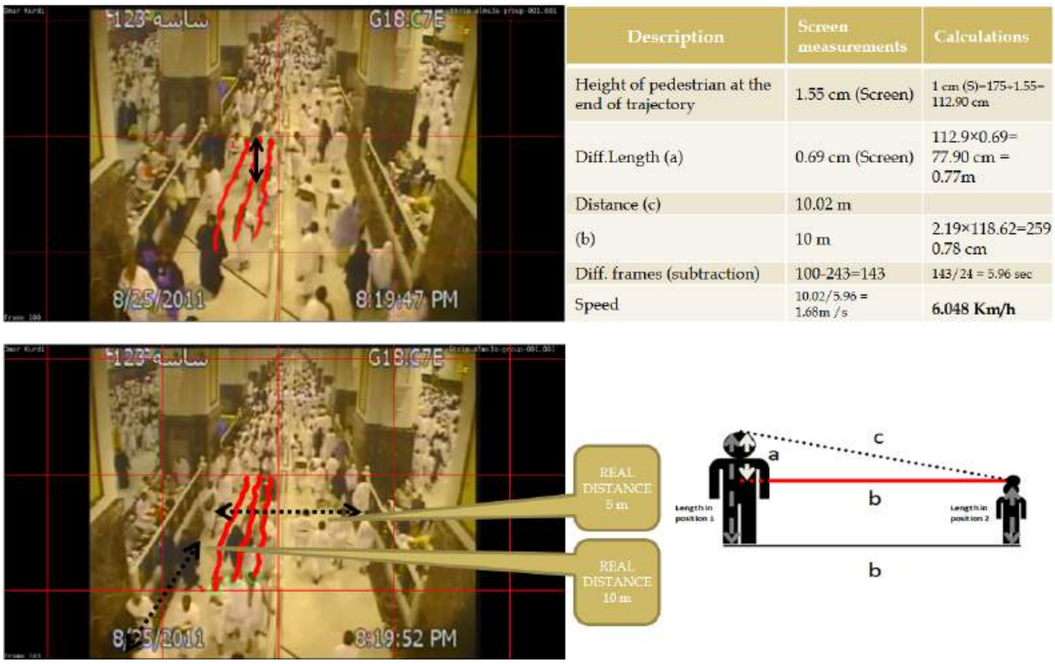
where, NF = number of total frames and FPS = frames per second

We compute the average agent speed (AAS) for each type of pedestrian as follows.

$$AAS_t = \frac{1}{n}\sum_{i=1}^{n} AS_i \tag{3.3}$$

where, t is the pedestrian type; $t \in \{individual, couple, group, elderly, young, disabled\}$; Si is the speed of the agent at ith measurement; and n = total number of the agent's speed measurements.

Figure 3.12 shows computation of speed using the length of an already known object, i.e. the length of the car in the video.



Description	Screen measurements	Calculations
Height of pedestrian at the end of trajectory	1.55 cm (Screen)	1 cm (S)=175÷1.55= 112.90 cm
Diff.Length (a)	0.69 cm (Screen)	112.9×0.69= 77.90 cm = 0.77m
Distance (c)	10.02 m	
(b)	10 m	2.19×118.62=259 0.78 cm
Diff. frames (subtraction)	100-243=143	143/24 = 5.96 sec
Speed	10.02/5.96 = 1.68m /s	6.048 Km/h

FIGURE 3.11: Extracting Speed From Real Video Footage

Description	Screen measurement	Calculated value
Car length	2.4 cm (S)	478.2 cm
1 cm (S)	1 cm	478.2/2.4= 199.25cm
Length of trajectory	4.05 cm (S)	4.05×199.25=806.96cm =8.07m
Frames diff (time)	272-107=165	165/30=5.5 sec
speed	8.07/5.5=1.46 m/s	5.26 Km/h

FIGURE 3.12: Extracting Speed From Real Video Footage by Using Known Object as a Scale Unit [124]

3.6 Agents Speed from Experiments

The speed of video recordings that is taken from Al-Masjid Al-Haram and Meadowhall Mall have been analysed and identified. Table 3.1 illustrates the values of the measured speed for different individuals as well as for the groups.

Table 3.1: Speed measurements for different individuals .

	Individuals speed (km/h)				
	Men	Women	Disabled	Old Men	Old Women
Average speed from literature [125]	5.38	4.83	5.38	4.63	4.55
Average Speed from Masjid Al-Haram videos	5.74	4.18	4.97	4.53	4.89
Average Speed from Meadowhall videos	5.41	5.26	5.11	4.93	4.21

The average speed of different groups has also been measured and analysed. Table 3.2 illustrates the values of groups average speed.

Table 3.2: Speed measurements for groups at different places.

Different social groups speed (km/h)				
	Individuals	Couples	Families	Group of 3 or more
Average walking Speed in Meadowhall	5.41	4.46	4.28	5.18
Average walking Speed in Masjid AL-Haram	5.74	5.33	4.96	5.33

3.7 Analysis of Crowd Behaviour from Real-World Videos

All video data [1] had been used to study the crowd behaviour have been collected from different closed and open environments (crowd behaviour of religious gatherings, behaviour within a centre of shopping and behaviour of students at universities) to obtain a diverse and visual crowd. The video recording observations helped to identify the different characteristics of groups and individuals along with the level of group impact through the interactions among individuals within the group. The observed behaviours of the individuals involved within various groups are listed in Tables 3.3 and 3.4.

[1] Available on http://www.muvet.ifsoft.ro/sayee/videos.html

TABLE 3.3: Individuals and groups noticed behaviours.

Individuals	**Group**
– Speed of a single individual is higher than the speed of the individual within the group, involving running. – Pushing others at higher density such as turning area. – Randomly stopping. – Follow the procession using visual perception during their move. – Walking throughout the groups for overtaking.	– Collision prevention among the groups. – The speed of groups is similar. – The speed of the group is reduced when a barrier come among the members or when waiting late member. – A leader is nominated for a group with four or more individuals. – When an obstacle is presented the members stop in a random way and then wait to pass the obstacle. – Absence of collision within the groups. – The distance inside the group is smaller than the distance among the groups.

The table above shows that a single individual/ agent has higher speed compared to groups of people. they also have tendency to stop in the middle of the walk as well as push others which creates obstruction to other individuals. further it is clear that a group is more co-ordinate with all the members of group having similar speed and groups maintain a distance among themselves as well as with other groups. families and couples also come under groups but they remain at a closer proximity compared to other normal groups. however, presence of a disabled greatly changes the overall dynamics of the group.

3.8 Introduction of Implementation

This section describes, in detail, the implementation of the Agent-Based Model (ABM) in the simulation of the crowd at Al-Masjid Al- Haram. During this implementation phase, several experiments were carried out (trials model screen shots shown in 3.13) to determine which platform should be chosen when building the simulation model. Only the summary of these trials is described, with the final implementation version of Netlogo and FLAME then described in greater depth.

TABLE 3.4: Samples of noticed behaviours among different groups.

Family Group	**Friends Group (three friends or more)**	**Couples (involve any two individuals)**	**Groups involving a disabled individual**
– Kids walk and run behind and front of their parents. – The prams are used to carry the luggage sometimes. – A distance is maintained between the family members with hands connecting. – A ring around the leader of the group is formed by the family groups. – Holding children hands or running to get them back to the group .	– The waiting time is varied among different group types. – The behaviour of loitering is displayed in this group.	– Generally they stay together and keep a minimal distance between them.	– The wheelchair is at the front of the group and no one walks in front of it. – The wheelchair moves in higher speed than the single individual's walking speed.

There were two candidates of agent-based modelling platform, namely FLAME and NetLogo. We selected these two platforms and wanted to see which platform would be best to use when building the simulation model. Netlogo was chosen owing to its capabilities in prototype initial models. The initial prototype developed in the Netlogo environment was more-or-less comparable to that of FLAME; the difference was that FLAME platform was considered more efficient in terms of modelling efficiency. Furthermore, the time was considerably reduced when using FLAME, and can be used to model large scale agent modelling cases as well. We carried out an implementation trial and performed the following experiments:

- A FLAME model with fixable agents to simulate *Tawaf* around holy *Kaabah*.
- A NetLogo model to simulate bidirectional corridor with two priority lanes for the disabled.
- NetLogo model to simulate *Tawaf.* The model simulated the behaviours of pilgrims, such as circumambulation, avoiding obstacles and others pedestrians, and entering and exiting the Mataf area.

- A NetLogo model with real environment and background simulation of *Sa'yee* ritual at Al-Masjid Al-Haram.

After completing the above-detailed experiments, NetLogo was chosen as the multi-agent simulation platform for the creation of the virtual world environment, along with extrapolation of the Netlogo developed prototype to FLAME, so that large-scale and generic modelling could be developed, as well as to create an interface for commands and procedures to be activated by the users of the software. The reasons for choosing NetLogo over FLAME are as follows: (1) greater efficiency and easier to use in developing non-complex models, where simulation time is not a factor; (2) improved visual capabilities, which enables easier visualisation in the simulation model; and (3) better documentation and help available through user community. We found that NetLogo was adequate in terms of implementing and simulating the formal models, whilst also enabling us to visualise their properties. Further, an expansion to the created model was performed in FLAME so as to increase its efficiency and decrease the processing time. The Netlogo model has been mapped to FLAME in collaboration with Dr. Ionut Niculescu. in Chapter 4 we presented results of and comparison in term of execution time.

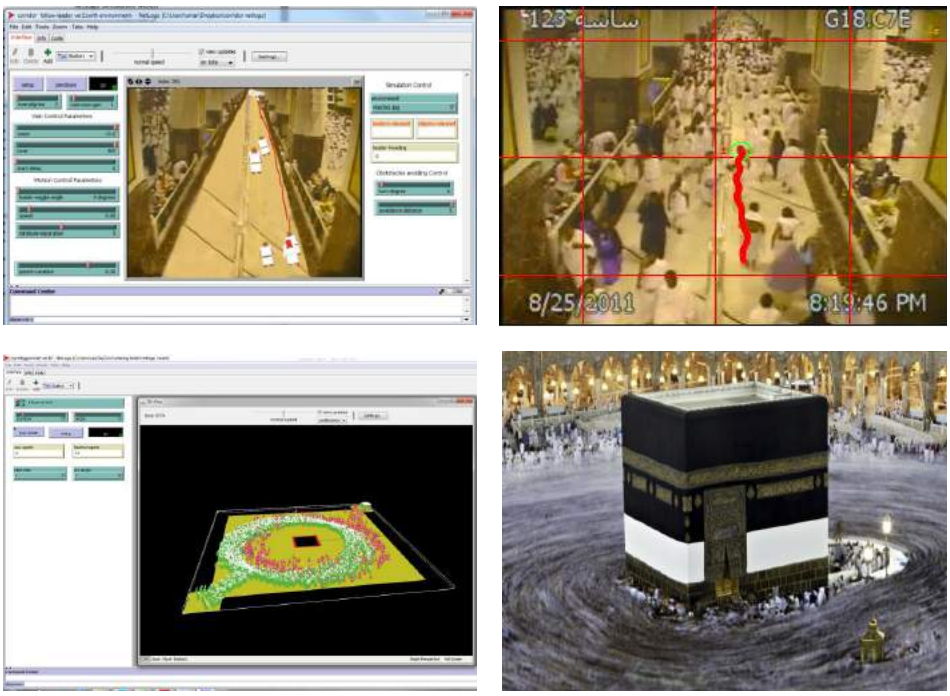


FIGURE 3.13: A screen shots of trials models appear on the left hand side and real photos of the cases on the right

3.9 Simulating the Sa'yee

NetLogo version 5.2.1, is used as the multi-agent simulation platform to develop the *Sa'yee* model proposed in this thesis. There are many online tutorials and a comprehensive user manual [126] on how to create, load and simulate multi-agent models using NetLogo. Here we are going to explain briefly how to simulate the *Sa'yee* model in NetLogo. Detailed information on the *Sa'yee* ritual and implementation of the model are given in Chapters 4 and 5. Figure 3.14 shows the main window of *Sa'yee* simulation model.

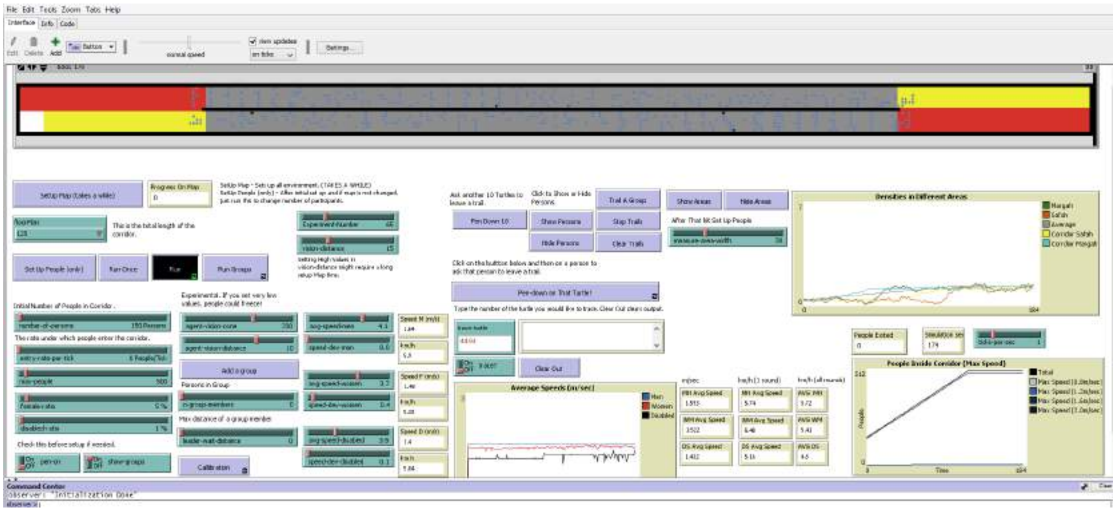


FIGURE 3.14: The main window of *Sa'yee* simulation model shows the control buttons of agents' behaviours

Firstly the user sets different simulation parameters, such as the floor plan, initial number of people in the corridor, the rate at which people enter the corridor, average speed of men, women and disable pilgrims, etc, as shown in Figure 3.14. After setting up these initial parameters, the user sets up the map and people (by clicking the buttons *SetUp Map* and *Set Up People*) for the simulation. The simulation can be run once, in batch and in groups. There are different output windows in the model where the user can see the output of different metrics, such as densities in different areas and average speeds during the simulation. The top most window shows the layout of the corridor of the *Sa'yee* ritual and the pilgrims as dots moving (performing the *Sa'yee* ritual) in the corridor.

The *Sa'yee* model proposed in this thesis is comprised of three floor plans that are 125, 205 and 345 meters in length which were built for shorten simulation cycle run time for faster testing behaviours purposes. The reasons for having these floor plans are: (1) To give a user the ability to choose a shorter floor plan and examine various behaviours using different parameters, and obtaining faster results, rather than using the actual floor plan. (2) This also provides more generality to the model so that it can be used with different corridor lengths.

By changing the model parameters, a user can simulate different scenarios of the *Sa'yee* ritual. This enables the user to observe different behaviours and dynamics of the pilgrims carrying out the *Sa'yee* ritual, without risking their lives. The data gathered during these simulations can help the user find the effect of change in group sizes, bottlenecks due to crowd density at various places (such as turning area, end of corridor). This is an efficient way to further help in the administration and management of the *Sa'yee* ritual, and in turn improves ritual performance.

3.9.1 *Sa'yee* Model Implementation

The main model of simulating *Sa'yee* ritual is implemented using NetLogo and TXstates library [127] that enables X-Machine execution in NetLogo. To model crowd at a microscopic level it is necessary to map all actions and motions of the crowd included in our research scope, then implement the members of the crowd as agents in NetLogo. To achieve this we carried out the following steps:

- We determined the scope of the model and targeted behaviours of members in the crowd;
- We extracted the characteristics of these behaviours from the recorded videos;
- We built an environment with similar dimensions correctly scaling it to the chosen model, then included other parameters to help improve the simulation runtime for testing purposes;
- We designed and drew the state transition diagram of the model (see Figure 3.10);
- We implemented the agents and their behaviours.

3.9.2 Model Assumption

The model is built based on the following assumptions:

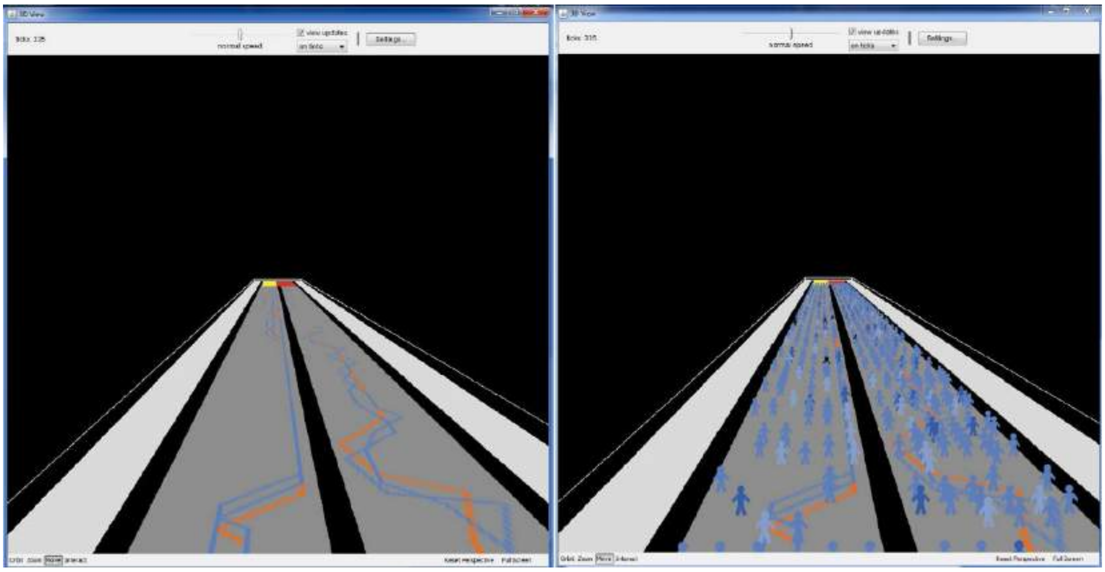
- We only consider the priority lanes for the disabled, as they are the most challenging area in the corridor.
- Any one can use the priority lanes for the disabled, depending on the lane density.
- All of the new pilgrims are only allowed to enter from the *Safa* side.
- The effects of all side doors in the corridor are lifted for a future work as the corridor have 16 doors, and incorporating their effects are beyond the scope of the research carried out in this thesis.

3.9.3 Behaviours Modelling

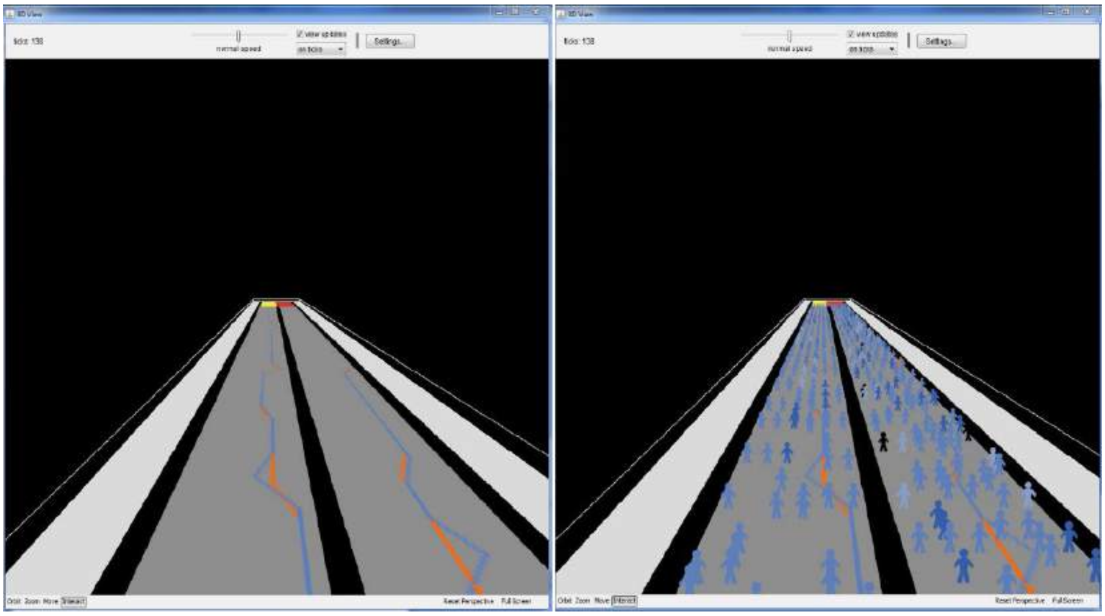
Innovating a model for the most common human behaviours presents a problematic and demanding issue. However, the behaviour of individuals within the crowd case are limited, where restricted actions are performed. Moreover, the behaviours and actions that affect the emerging crowd behaviours only involves a small number of human behaviour and actions. A simulation model of a corridor has been suggested which principally focuses on the behaviours of disabled pedestrians during their walk in a two way corridor with different crowd densities. Pedestrian movements are most often initiated based on particular intentions and decisions. To simulate these dynamics, movements of microscopic level should be implemented. Environmental events and parameters that are performed during these movements may recognize new choices and actions. Within this experiment, the following behaviours have been noticed and chosen;

- Overtaking
- Grouping
- Walking with different speeds
- Following the leader
- Avoiding disabled wheelchairs and obstacles.

Figure 3.15 illustrates a view of the *Sa'yee* simulation model and the key parameters of movement. X-Machines have been used to model the behaviours of agents within this work. Generally, three individuals or agent types are simulated in the pedestrian model. As shown within this work, by these three standard types, the full individual diversity within the actual-world scenario of crowds can be simulated. These types are.



(A)



(B)

Figure 3.15: A view of the simulation model showing different behaviours/movements of the crowd members.

- Individuals; represent the agents who do the ritual separately. Also, it involves the disabled individuals. The individual population has a changeable maximum speed, however the behaviour of all individuals is the same.

- Leaders; represent the agents who direct and lead a set of individuals within the corridor. The leaders group members are near to each other and wait for the members left behind. On the other hand, the behaviour of these members is the same as that of individual behaviours.

- Followers; represent the group members who follow the group leader. The behaviour of these members when they lose contact with their leader is the same as that of the individual behaviour until they find their group or finish the ritual.

3.9.4 Agents

The entrance area is where agents first enter the simulation environment. After entering, they move towards the turning area and enter the corridor. Once inside the corridor, they move towards the neighbouring exit area of the corridor. When agents reached the exit area they record this event in their memory. The agents then change their state accordingly, and move towards the turning area that is close to the exit where the agent is currently located. When agents reach the turning area they again move towards the corridor. These steps are executed 7 times based on real behaviour.

There are three types of agents in the simulation:

- *Individuals* are single agents performing the ritual alone. Each individual has a different maximum speed, but exact behaviour.

- *Leaders* are agents that guide a group of individuals in the corridor. Leaders wait for members of their group, and when one such member is at a far distance they reduce their speed, but never stop completely even if all members are lost. Leaders resume their speed when all members are near, and contrarily adopt the same behaviour as individuals.

- *Followers* are member of a group that follows a leader. When inside the main corridor area, followers simply try to move closer to the leader. At exits, followers temporarily *break away* from the leader assuming the same behaviour as individuals until they reach the turning area, after which they resume their standard behaviour. If followers cannot detect their leader in a rather large area, they then assume the role of an individual, i.e. perform the ritual alone, until either they complete the ritual or again find their group. This design implementation was adopted to avoid the freezing of agents due to loss of contact with their leader, and thus blocking the movement of other agents.

3.9.5 Agents Density Measurement

The density of pedestrians during the performance of *Sa'yee* has been measured. This scenario involves different types of pedestrians: men, women, children and the disabled. The density has been measured based on the number of pedestrians entering the corridor per second, for a time duration equal to 32 seconds from six different videos. The number of pedestrians entering during this duration has also been measured. The results show that the average number of pedestrians per second was equal to 2.97. The details of this scenario are shown in figures 3.16 and 3.17. The entering timings of different types of pedestrians were measured by following the pedestrians using tags as shown in Figure 3.17. The measured numbers of different type of pedestrians entering the corridor are shown in Figure 3.16.

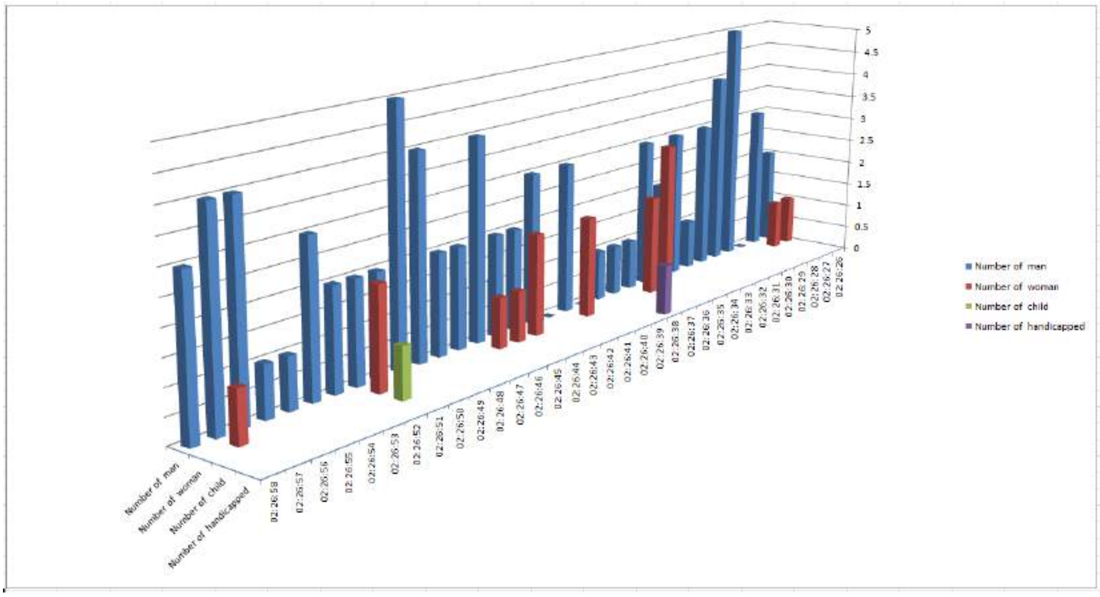


FIGURE 3.16: Counting pedestrians for measuring their entering time to compute crowd density (entering rate) in the corridor from one of the videos. The X axis represents time of each frame and the Y axis represents the number of pedestrians classified as men, women, children and disabled.

FIGURE 3.17: Counting number of pedestrians passing solid line (shown as red line with tag as arrows) to calculate crowd density.

3.9.6 Agent Vision

A visual representation of agent vision is shown in Figure 3.18. At initialization of the environment we compute a set of visible cells (patches) and the free positions that the agent can move to as shown in Figure 3.19. Walls are represented by black cells and agents by circles. An agent can see behaviours like, slowing down due to congestion in the corridor, and overtaking from a certain distance called the *vision-distance*. Thus each such set contains the patches that are viewable, given that the agent has a *viewing-distance* equal to the *vision-distance*. This allows easy modelling of an obstructed vision of the agents. Computing visible patches is expensive, and thus is done only once while setting up the simulation. The larger the radius (the *vision-distance*), the more time it takes to compute the set of visible patches. If the agent has a smaller *vision-distance*, the same set can be used without modifications, as shown in the description of the agent movement that follows.

3.9.7 Agent Motion

Each agent occupies a single cell at a given time and can move forward, left, or right from one cell to another, overtaking other agents and obstacles. An agent can move multiple cells in one tick. Each tick is 1 sec and one cell is $0.4m^2$, thus an agent can have speeds that are a multiple of 0.4m/sec. The set *ANP* is all the accessible next positions an agent can move to in relation to its current speed *S*, and consists of all the adjacent free

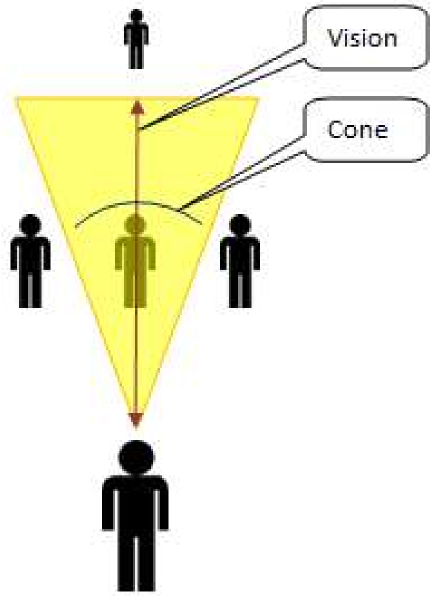


FIGURE 3.18: The agent vision

cells (that are not occupied by other agents) the agent can reach in S jumps from its present position AP. We compute this recursively, to cover all the valid paths that exist from the agent's present position (AP) to all the accessible next positions that the agent can move to (the set ANP).

Figure 3.19 shows an example of computing the motion of an agent represented by a black coloured circle in the Figure. The agent's movement is restricted by walls (in black) and the presence of other agents (shown as circles). The free positions (the set ANP defined above) of an agent are shown in gray colour. The speed of the agent is 2, and can move two arrows or two free cells (positions) in one tick. These free positions are the positions that are in the *vision-cone* (shown in Figure 3.18) of the agent.

Each Agent selecting the shortest route that extends between the two ends of corridor with a stochastic wiggle angle depend on the free cells available on its vision.

3.9.8 Agent Speed

In our simulations, we consider the following populace of agents: either single agents or agents walking together as groups through the corridor, three types of agents, women, men and disabled persons. They are characterized by their walking speeds. Table 3.5 reports the average speed values for these three types of agents as measured from recorded

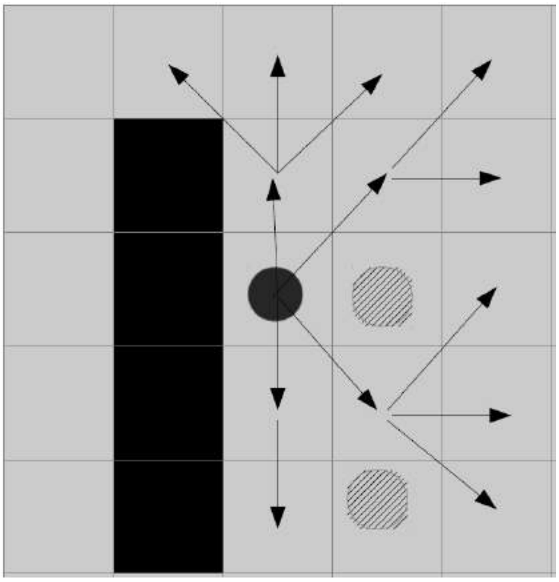


FIGURE 3.19: The free positions (the set ANP) an agent can move to, with the speed set to 2 cells.

videos – first row – and as reported in [3] – second row. We start with walking speed of the agents, which are close to the average values provided in Table 3.5. We notice that the average speed (during simulation) is below the values provided in Table 3.5, due to the slow down in speed whenever there is congestion. Therefore, we allowed in the simulation model for the agents to walk at a higher rates of speed. The issue here is how to choose (calibrate) these values and then distribute them across the three categories of agents. The following section addresses this problem.

TABLE 3.5: Average speed values (in km/h) for three types of agents. The speeds in the first row are measured from the videos, and the speeds in the second row are reported in [3] and are measured using a stop watch.

Men	**Women**	**Disabled**
5.74	5.18	4.97
5.38	4.83	5.38

3.9.9 Agents Interactions Rules

How the members of an ABM interact i.e, the way they communicate with each other is very crucial in designing the ABM. The agents in an ABM are a part of a community, similar to the members of a crowd, and some of the forms of interactions in the two can be common, such as, talking or shouting, and elbowing or outright pushing, etc. These forms of interactions depend upon the specific case under study. For example, in a crowd performing the *Sa'yee* ritual, if the crowd density increases to a certain limit, the crowd members can push each other and this in turn can cause a stampede.

To simulate the pedestrians interactions the following rules have been adopted:

- Select the shortest route that extends between the exit and entrance with a stochastic modifiable wiggle angle (see trajectory in Figure 3.26).
- The speed of walking is modified based on two parameters of average speed and speed deviation.
- The distance between the pedestrians should not exceed the certain threshold, and if it exceeds the leader must reduce the speed to maintain the distance to followers.
- Selecting the number of group members based on the average group member observed from provided videos.
- Only one leader is allowed for each group.
- The speed of pedestrians will be varied from one pedestrian to another via speed deviation parameter that aims to increase the pedestrians' speed and decrease it with maintaining same average(depending on the pre setted speed value).

3.9.10 Goal Sharing

Goal sharing is a very important feature of ABM. All the agents in an ABM are designed so that actions lead towards the realization of this common goal. Similarly in a crowd, all the crowd members can be said to possess a goal, and in a common environment this goal becomes a common goal for all the crowd members. The condition is that the environment should be precisely defined and have common characteristics towards the crowd members. For example, a crowd performing the *Sa'yee* ritual can be said to possess a common goal.Similarly, a crowd in a riot or an escaping crowd share a common goal of escaping.

3.9.11 State Transition Diagram Specification

The most important aspect of the TXstates is the ease by which states and transitions between states are encoded, since it allows directly encoding X-Machines in NetLogo. A single state and the related transitions are encoded as:

```
state <StateName>
# x-func <XMachineFunction 1> goto <StateName 1>
...
# x-func <XMachineFunction n> goto <StateName n>
end-state
```

where *<XMachineFunction>* is a NetLogo X Function (reporter) and *<StateName>* is the name of the target state of the transition (a simple string).

An X-machine that consists (as usual) of multiple states is in fact a NetLogo list of such state definitions:

```
x-diagram
state <StateNameA>
# x-func <XMachineFunction A1> goto <StateName A1>
...
# x-func <XMachineFunction An> goto <StateName An>
end-state

state <StateNameK>
# x-func <XMachineFunction K1> goto <StateName K1>
...
# x-func <XMachineFunction Kn> goto <StateName Kn>
end-state
end-diagram
```

In such a specification, the first state that appears in the list is considered to be the initial state. Executing the agent specifications presented in the previous section is the responsibility of the TXstates meta-interpreter.

3.10 State Transition Diagram

The state diagram of the agents is shown in Figure 3.20. This state transition diagram is directly encoded in NetLogo, using the domain specific language (DSL) TXStates. The initial state of the agents is marked as *Entering* and the final state as *Exiting*, i.e. the agents are considered to have left the simulation in this state.

The state transition diagram of Figure 3.20 implements the following agent behaviour. An agent enters the entrance area of the simulation environment. She/he then heads towards the turning area in front and walks to the end of the corridor. After entering the corridor the agent moves towards the exit area adjacent to the specific corridor. When the agent reaches the exit area she/he records this fact in memory, changes her/his state, and heads towards the turning area that is located close to the exit in which the agent is currently situated. Upon arriving at the turning area the agent again moves forward towards the corridor. According to the ritual these moves are carried out seven times.

3.10.1 X-Machine Memory Management

At the time of agent creation the variable must be initialised and appropriate memory positions (attributes/variables) must be created. The following TXstates commands are used to accomplish this:

- *x-init-memory*. It initialises memory to an empty structure, and is only invoked once.
- *x-mem-initial-var <varName> <Value>*. It adds a new X-machine variable value pair to the memory. The first argument <varName> is a string representing the name of the memory position and the second argument (<Value>) is its initial value.

For example, the following code initialises X-Machine memory and creates variable value pairs. The variables *leader* set to false, *turns* set to 0 and *speed* being a random value from the list (2, 3, 4, 5).

```
...
init-x-memory
x-mem-initial-var "leader" false
```

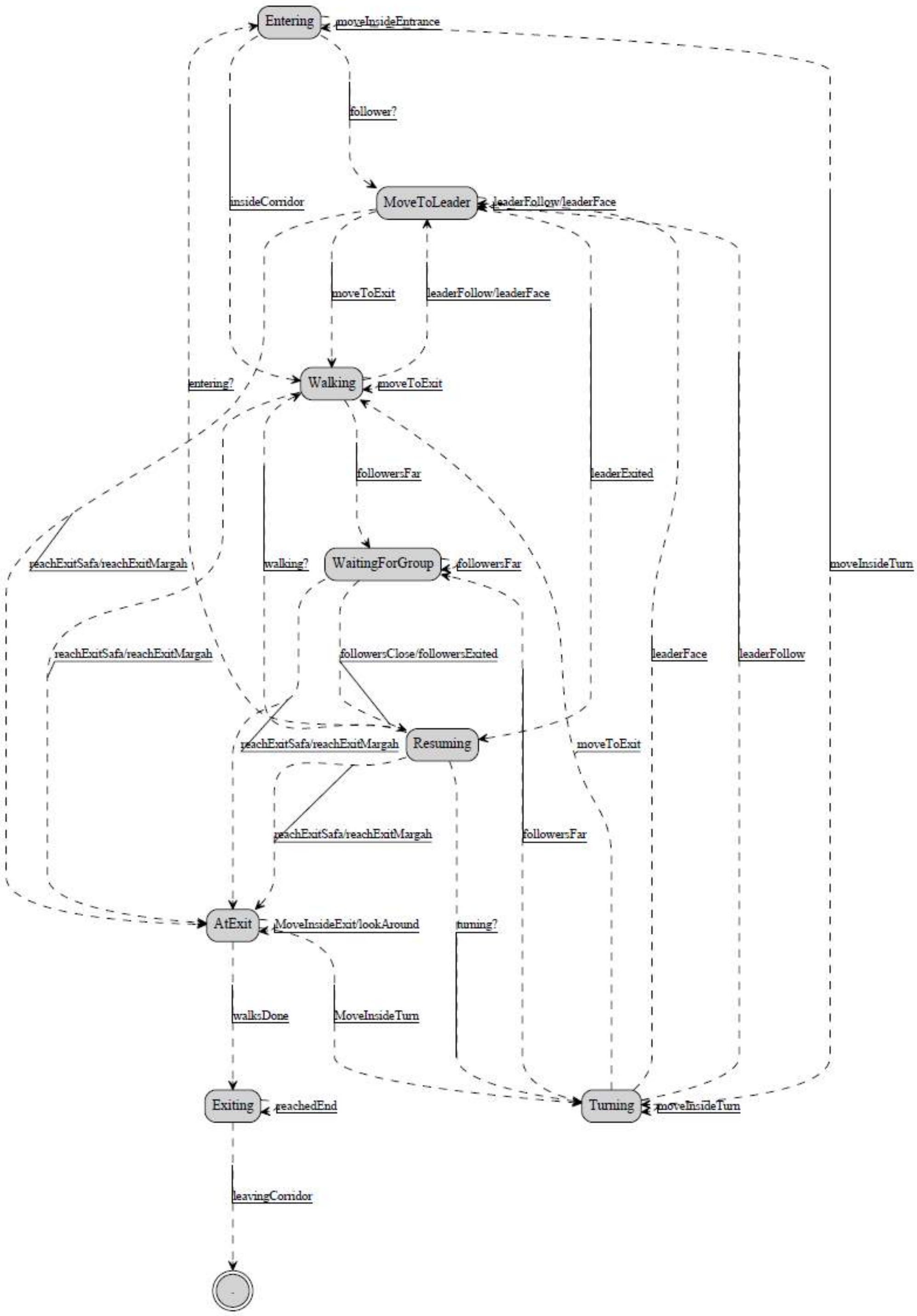


FIGURE 3.20: State transition diagram.

```
x-mem-initial-var "turns" 0
x-mem-initial-var "speed" one-of [2 3 4 5]
...
```

Accessing memory variables is achieved by calling the function (NetLogo reporter) *x-mem-value <varName>* anywhere inside the code of the agent. For instance a call *x-mem-value "turns"* anywhere after its initialisation through *x-mem-intitial-val* will return the value 0. Updating memory variables can only occur from an X-function (see section 3.10.3) and thus during X-Machine execution. TXstates library provides the command *x-mem-set <varName> <Value>*, for such destructive updates.

A call *x-mem-value <varName>* returns the value of <varName> which after initialisation is always 0. The X-function *x-mem-set <varName> <Value>* sets or updates the value of the <varName> to <Value>. For example, the following code updates variable *leader* to true and increases the value of *turns* by one.

```
...
x-mem-set "leader" true
x-mem-set "turns" x-mem-value "turns" + 1
...
```

The *x-mem-set* command can appear only as a part of an X-Machine function, since according to the model, only X-functions can change memory values. If the user uses *x-mem-set* in any other place than as a *return* value of an X-function, the results will not be as expected.

3.10.2 Input

Each X-Machine input, i.e. agent percepts, is modelled as an attribute-value pair (tuple, <P> <Val> in the following), and there can be multiple values for an attribute, i.e. multiple tuples. The list of primitives is the following:

- *x-add-percept <P>*, adds a percept <P> with no value. The percept in encoded as a tuple carrying the dummy value *x-nil.*
- *x-percept-add-value <P> <Val>*, adds a percept <P> with value <Val>.
- *x-has-percept? <P>*, returns true if there is a percept <P> in input.
- *x-percept-value <P>*, returns the value <Val> of the percept <P>. In the case of multiple tuples for the same percept, the first value is returned.

- *x-oneof-percept-value* <*P*>, returns a random value <Val> of the percept <P>, in the case that there are multiple tuples for <P>.
- *x-all-percept-values* <*P*>, returns all values of <P> in a list.

3.10.3 X-Functions

X-Functions are encoded as NetLogo reporters, called functions in NetLogo. These functions do not have any arguments. They have access to input, output and memory and hence operate on input and memory and produce output and memory updates. The return value of these functions is either a *success token* followed by output and memory updates or a *failure token.* The TXstates meta-interpreter uses these values to determine the possible transitions. The token values are either:

- *x-false*, a keyword handled by the meta-interpreter, indicating that the function is not applicable,
- *x-true* <*xmOutput*> <*xmMemUpdates*>, indicating an applicable function that will produce <*xmOutput*> output and change memory according to the <*xmMemUpdates*>.

The first argument <*xmOutput*> of *x-true* is a list of actions that the agent has to perform. The second argument <*xmMemUpdates*> is a list of memory updates.

There are no limitations regarding the code that these functions can include as long as it respects the X-Machine simulation semantics. The meta-interpreter evaluates (runs-tries-executes) all functions, producing possible memory and output results, and then decides which function to apply. The following is an example of an X-function encoded as a NetLogo reporter. The function checks whether the agent has certain percepts, executes the NetLogo procedure fd 1 and updates the memory variables *turns* and *half Cycle*. Note that since memory updates are a list, the first *x-mem-set* will use the previous value of *half Cycle* and then set it to 0.

```
to-report reachExitSafa
ifelse has-percept-type "exitReached"
[report x-true
#< x-action task [fd 1] >#
```

```
#< x-mem-set "turns" (x-mem-value "turns" + x-mem-value "half Cycle")
x-mem-set "half Cycle" 0 >#]
[report x-false]
end
```

X-Machine functions control state transitions and memory updates. They are encoded according to the TXStates DSL. For example the function *leaderFollow* listed below implements the strategy of the follower agent. The agent tries to move closer to the leader, if there is a leader in an area that can be seen, and a free-position is available near to the leader. It should be noted that the leader can be in the area of vision of an agent, but the agent may not be able to see her/him, because she/he is focusing in a different direction.

The output of the above function is the following actions. The agent move to a specific position closer to the leader and updates memory reflecting the change in her/his position.

```
to-report leaderFollow
ifelse x-has-percept? "leader-in-area" and x-has-percept? "closer-to-leader"
and x-has-percept? "can-see-leader"
[report x-true
#< x-action task [person-move x-percept-value "closer-to-leader"]
>#
#< x-mem-set "position" x-percept-value "closer-to-leader" ># ]
[report x-false]
end
```

The following example function *reachExitMarwah* counts the number of cycles when reaching the exit *Marwah*.

```
to-report reachExitMarwah
ifelse x-has-percept? "exitReached" and x-percept-value "exitReached" = "Marwah"
[report x-true #< >#
#< x-mem-set "turns" (x-mem-value "turns" + x-mem-value "halfCycle")
x-mem-set "halfCycle" 0 >#]
[report x-false ]
end
```

The following function *moveToExit* enables the agent to manoeuvre nearer to the corridor exit and thus implements the agent's "walking" strategy. If the agent is inside the corridor (*corridorReached*) and can perceive a position closer to the exit, the agent moves to that position.

```
to-report moveToExit
ifelse x-has-percept? "corridorReached"
and x-has-percept? "closer-to-exit"
[report x-true
#< x-action task [person-move x-percept-value "closer-to-exit"] >#
#< x-mem-set "position" x-percept-value "closer-to-exit" >#
]
[report x-false ]
end
```

3.10.4 Agent Variables

Each agent, also a turtle in NetLogo, must carry its own state and memory information. The state and the memory information of an agent is stored in variables, called agent-own variables. There are two types of variables. The first type are used internally and should not be changed by the developer, because they hold information about state code, state transitions, etc. These variables are: *active-states*, *active-states-code*, *active-machines* and *active-machine-names*. The second type consists of those variables that the model under development should update/change in each execution cycle. These are: *memory*, *percept* and *emotion*.

For specifying the behaviour of an agent using X-Machines the corresponding agent in NetLogo should define the above mentioned variables. For instance, if we are to create agents of the breed *persons* driven by an X-machine, the NetLogo code is:

```
persons-own [active-states active-states-code active-machines
active-machine-names memory percept emotion]
```

3.10.5 Environment Preparation

The model simulates pedestrians moving back and forth seven times in the corridor between the two holy hills of *Safa* and *Marwah*. The corridor has an approximate length of 300m excluding the turning area, and two disabled priority lanes, each being 2.5 meters in width. The corridor layout is shown in Figure 3.22. Based on the assumptions

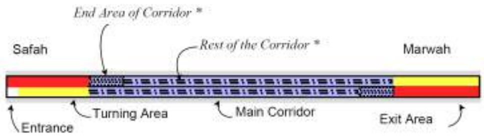


FIGURE 3.21: The Corridor under Simulation in NetLogo [2].

described above, three different sizes of the layout were developed in NetLogo and described below. We used *mtPaint* available at http://mtpaint.sourceforge.net, an open source painting program to create pixel art, and develop these layouts in the model.

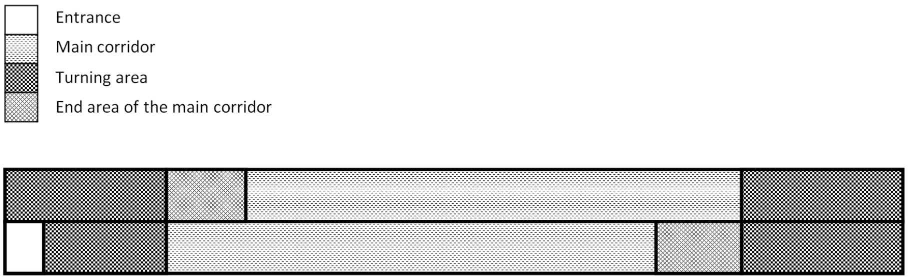


FIGURE 3.22: The corridor layout

- The first has a length of 125m, and includes the the size of the turning areas (the areas near *Safa* and *Marwah*) and the width of the corridor.
- The second has a length of 205m and includes the turning areas and the corridor length.
- The third has a length of 345m and includes the turning areas and the full corridor length.

The simulation environment consists of four areas, denoted by different textures in Figure 3.22.

- The *entrance area*, the point by which an agent enters the simulation, is depicted in white.
- The *turning area*, the area where agents turn at the *Safa* or the *Marwah* end in order to walk back to the corridor.
- The *main corridor*, the area where agents walk, is depicted in dashed-lines.

- The *exit area* indicates the exit of each corridor. It should be noted that in the simulation, patches in the exit areas of *Safa* and *Marwah* are annotated by the name of the corresponding hill. The annotation is an assigned value to each patch, and denotes the specific exit.

The length of the corridor 300m is equal to 750 patches (750 x 0.4m = 300m), and the two lanes are 6 patches wide (6 x 0.4m = 2.4m), where as the middle section that separates the two lanes is 1 patch wide (0.4m). Details of the dimensions of the areas are shown in Figure 3.23.

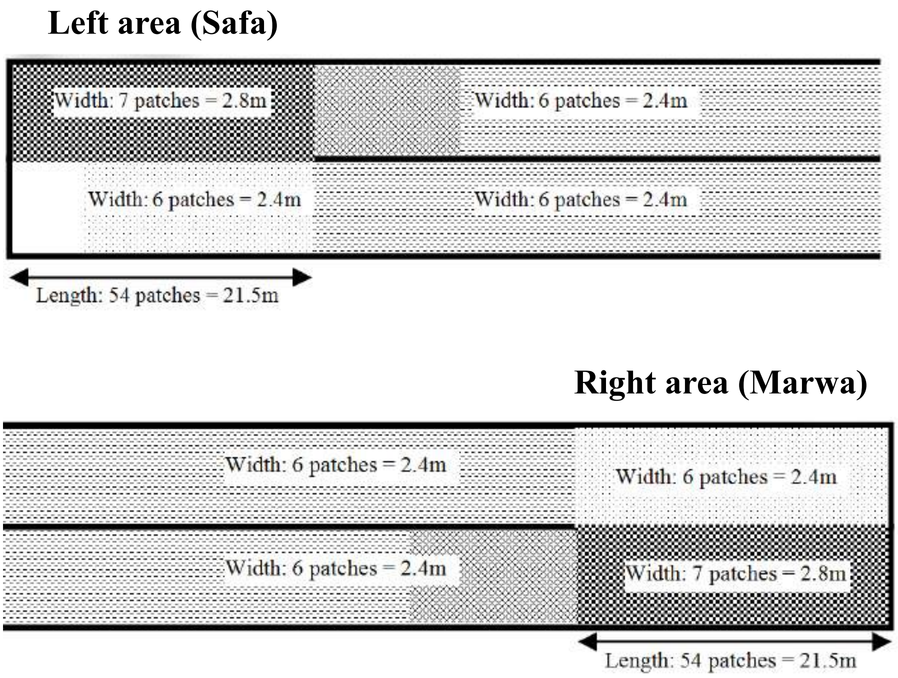


FIGURE 3.23: The corridor dimensions at the ends of both sides

3.10.6 Information Stored in the Environment

In order to facilitate implementation, each patch has some information encoded that helps either the movement of agents, or measuring of the density. This is stored in a patch-own variable, i.e. as information stored in the specific location. The variables are:

- *visible-patches*, the set of patches which are *visible* by the current patch (See Section 3.9.6)

- *hill-name*, is a value that indicates whether the patch is located in one of the exits (*Safa*, *Marwah*). Patches that are not exits have a value of 0.
- *nearest-exit*, is defined for all patches. Its value is the patch at the far end of the corridor, i.e. on the left for the corridor leading to *Safa*, and on the right for the corridor leading to *Marwah*. This helps agents *navigate*.
- *nearest-turn*, this is defined for exit points only (Black and white square areas as shown in Figure 3.22) and is a patch on the *other side* of the corridor, i.e. it points to where agents should be directed in order to reach the other side, in other words turn.
- *is-near-to*, this variable gets one of the values (*Marwah*, *Safa*, *Corridor Marwah*, and *Corridor Safa*) and is used to measure densities.

The following is an example of the use of the above variables. If the agent is located somewhere inside the main corridor, then she/he has to move as close to the exit (*Safa* or *Marwah*) as possible. We assume that there is a function that returns all possible free-positions according to the agent's own speed. Out of all these positions located inside the main corridor or at an exit, the agent must go to the one that is closer to its *nearest-exit*. The code is as follows:

```
let my-exit nearest-exit
let targ min-one-of (free-positions my-speed)
with [is-main-corridor? or is-exit?] [distance my-exit]
```

The above simply reads *targ is one of the patches in the set {free-positions, my-speed} that is either a patch in the main corridor, or a patch at the exit and is closer to the nearest exit in the corridor*. Thus an agent by inspecting the *nearest-exit* variable of the patch, can always direct herself/himself to the right position in the corridor.

3.10.7 X-machine Input

Input to the X-machine triggers functions and state transitions, and represents the agent percepts. The possible inputs to the agents are as follows:

- *leader-in-area*, when the leader is in an area visible to the agents.
- *leader-exited*, when the leader has exited the simulation.

- *can-see-leader*, when the follower can see the leader.
- *leader-close X*, X being a free position (patch) that the agent can move to according to the agent's speed, and X is closer but not in front of the leader.
- *follower-far*, when one of the members of the group following a specific leader is located at a distance greater than a threshold.
- *followers-exited*, when all followers of a leader have exited the simulation.
- *exitReached (Safa | Marwah)*, when the agent has reached one of the two exits from the corridor area.
- *X closer-to-turn*, X being a free position closer to the turning area.
- *endReached*, when the agent has reached the area from which she/he can exit the simulation environment.
- *closer-to-exit*, a free position closer to the exit.
- *entranceReached*, when the agent is located inside the entrance.
- *closer-to-corridor X*, X being a position closer to the corridor.
- *corridorReached*, when the agent is located inside the main corridor.
- *turnReached*, when the agent is located inside the turning area.

3.10.8 Memory

A number of memory positions, or parameters, allow the modelling of a varied population using a single X-Machine model. These parameters are initialized at the time of agent formation, and revised through X-Machine functions. The list of memory variables are:

- *Position*, the current position of the agent.
- *Speed*, the current speed of the agent. In some cases leaders may reduce their speed to wait for the group. This variable is also used to determine the available free positions that the agent can move to.
- *Max-speed*, the maximum speed the agent can walk. This variable is not changed during the simulation.

- *Gender*, indicating a male or female agent.
- *Leader*, which indicates that the agent is a leader of a group (value true/false).
- *Follower*, indicates the agent is part of a group, i.e. is following a leader (value true/false)
- *Follow*, if the agent is a follower, then this variable holds the id of the leader (I know who I am following).
- *Followers*, if the agent is a leader, then this is the set of its followers.
- *Turns*, the number of turns the agent has completed.
- *HalfCycle*, the variable is set to 1, when the agent has reached exit *Marwah*. It is used to count pedestrian cycles, ensuring that the agent has completed a full cycle in the corridor.

3.11 Software Tools Used

The choices of software tools greatly alters the performance and efficiency of any system modelling. the success of such a complex simulation should thus incorporate correct selection of tools and software also a simulation takes several steps to complete. those steps described in flowcharts of method in section 3.3. A brief introduction of all the tools used in the simulation are discussed below:

- Video editing tools, such as Windows moviemaker [2] and Blender [3] .
- Pedestrian trajectory extracting tools from videos, such as Petrack [4].
- Measuring (objects on the screen) tool, such Meazure [5].
- Environment building tools for the simulation model, such as MtPaint [6].
- Agent based simulation tools, such as Netlogo [7].

[2] www.windows.microsoft.com/en-us/windows/movie-maker
[3] www.blender.org/
[4] www.goo.gl/gw3os9
[5] www.cthing.com/Meazure.asp
[6] www.mtpaint.sourceforge.net/
[7] www.ccl.northwestern.edu/netlogo/

- Domain specific language tools to facilitate encoding and execution of X-machine, such as TXstates Library [8].

3.11.1 Blender

Blender [128] is an open source 3D software for computer graphics animation. It is used for creating animated movies, interactive 3D applications, video games and video editing, etc. When Blender is started, a splash screen appears as shown in Figure 4.5. The blender window is organized into one or more *Editors*. An *Editor* provides a way to display and modify different aspects of the data.

Some of the editors available are: *Graph Editor*, the main animation editor that allows the user to modify the animation; *Movie Clip Editor*, can be used for masking or tracking movies; *Video Sequence Editor*, a complete video editing system that allows the user to combine multiple video channels and add effects to them; and *Text Editor*, a text window that provides different text editing capabilities, such as cutting, copying, pasting, loading and saving, etc.

Blender is used in this thesis to reduce video clips of case studies to sequence photos, that are then used in PeTrack software to extract pedestrian trajectories. The Video editing (*Video Sequence Editor*) feature of Blender is used to accomplish this. Figures 4.5, 3.24 and 3.25 show the steps for extracting the image sequences from one of the video clips used in this thesis.

First the video clip is loaded into Blender as shown in Figures 4.5 and 3.24. Then, after selecting the number of sequence images to be extracted from the video, animation is carried out to extract the sequences. Blender saves these sequences on the disk. For the video clips used in this thesis, we found the following formula for computing the number of sequences, to be used in PeTrack, from a video clip: (Length of the video clip in seconds) $\times 30$ (fraperme rate of video camera is 30 frame/second). For example for a video of 10 seconds 300 sequence images were extracted.

We use PeTrack to extract a pedestrian trajectory from these sequences. To accomplish this, the first of these sequences is loaded into PeTrack as shown in Figure 3.25. A

[8] www.users.uom.gr/ iliass/projects/TXStates/

FIGURE 3.24: One of the video clips used in this thesis is loaded in the video editing window for extracting the image sequences.

pedestrian is selected to be tracked by marking the pedestrians head with a circle, and then PeTrack is used to automatically extract the trajectory.

FIGURE 3.25: The first sequence of images with one of the pedestrians' heads selected (in a circle) is loaded into PeTrack for extracting the pedestrian trajectory.

3.11.2 PeTrack

PeTrack (Pedestrian Tracking) [63, 129] is an open source software tool written in C++ that supports both Windows and Linux platforms, because all of these it was chosen in our methodology. Instead of using the manual procedures, which are time consuming and do not provide sufficient accuracy in space and time, we used PeTrack to collect the data from the recorded videos, to understand and model the *Sa'yee* ritual crowd. This empirical data greatly helped us to analyse and verify the crowd members' movements trajectories.

PeTrack provides the user with the ability to extract the trajectories from special video recordings. In these recordings, pedestrians in the videos must wear a special marker cap that is automatically detected by the software as shown in 3.26. The angle, distance and specifications of the camera, that is used for the video recordings, are measured. All these measurements enable the software to mathematically calculate the speed of the pedestrians. However our case we used this software for tracking pedestrians' heads from real life videos with an unknown camera angle, distance and specification. Due to these limitations the calculation of the pedestrians' speed have been done manually using a different technique (described in section 3.5).

The main window of PeTrack is shown in Figure 3.25. After importing a video or an image sequence, the first image will be shown in the top left area of the application. The navigation through the image stream is done below the image. On the right of the image, zooming and rotation is possible. The status line in bottom-most area gives information about the pixel under the mouse. If the calibration is done correctly it displays the colour, pixel row, column and the real world position of the specified height.

3.11.3 Extraction of Trajectories

To extricate very precise trajectories from video recordings PeTrack performs the following tasks.

- **Calibration** - To extract measurement information the video has to be undistorted. To remove distortions from the video the automatic calibration method introduced in [129] is used. A tab on the tool main window provides the user with the capability of manually entering the intrinsic parameters of the camera model.
- **Recognition** - After the undistorted video is obtained, persons in a single frame with special markers are recognized. To make this process completely automatic a special stereo camera is to be used for the recording videos.

- **Tracking** - After recognizing, the persons (pedestrians) have to be tracked. The tool allows for repetition of the tracking and different quality levels for the repetition, and allows the user to insert any frames missed while recording.

- **Height Detection** - The knowledge of every persons' height is required to correct the perspective distortion, . Height is detected during the recognition process using colour markers (see Figure 3.27).

The main settings for the steps of trajectory extraction have to be done on the tabs (Figure 3.26); calibration, recognition, tracking, height detection and analysis, reciprocal to the steps of the processing pipeline of the trajectory extraction. The analysis tab allows some direct analysing tasks of the trajectories. Figure 3.26 shows PeTrack example output of extracted trajectory.

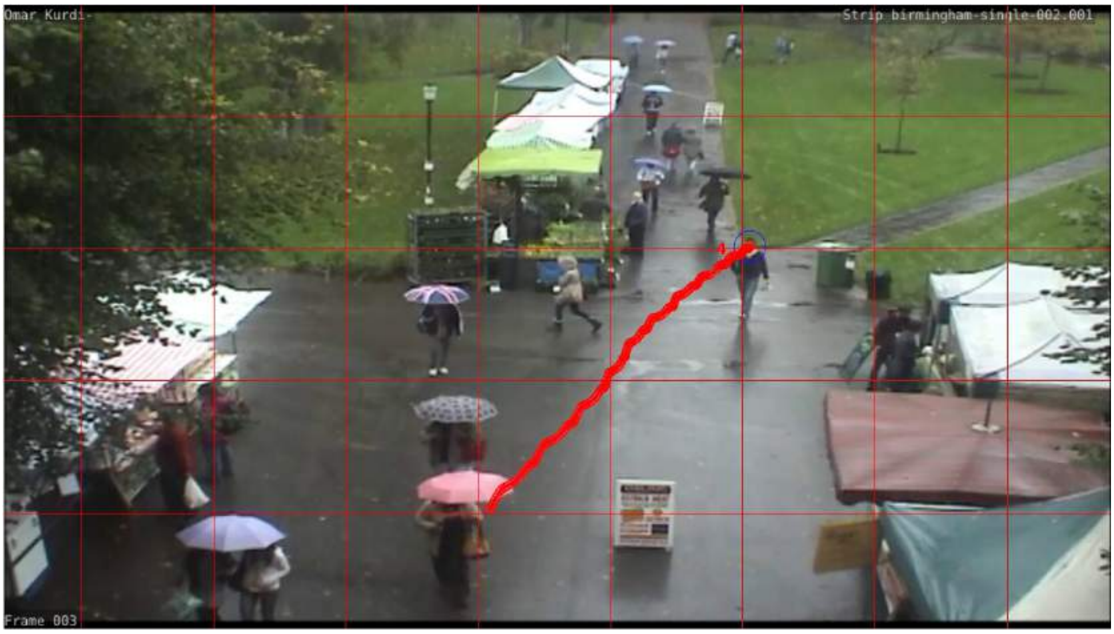


FIGURE 3.26: An example trajectory extracted using PeTrack.

3.11.4 Meazure

Meazure [123] is an open source software tool written in C++ that magnifies, measures and captures the screen by implementing a number of features. The current stable version of Meazure 2.0 used in this thesis supports the Windows platform only. Some of the features provided by Meazure are:

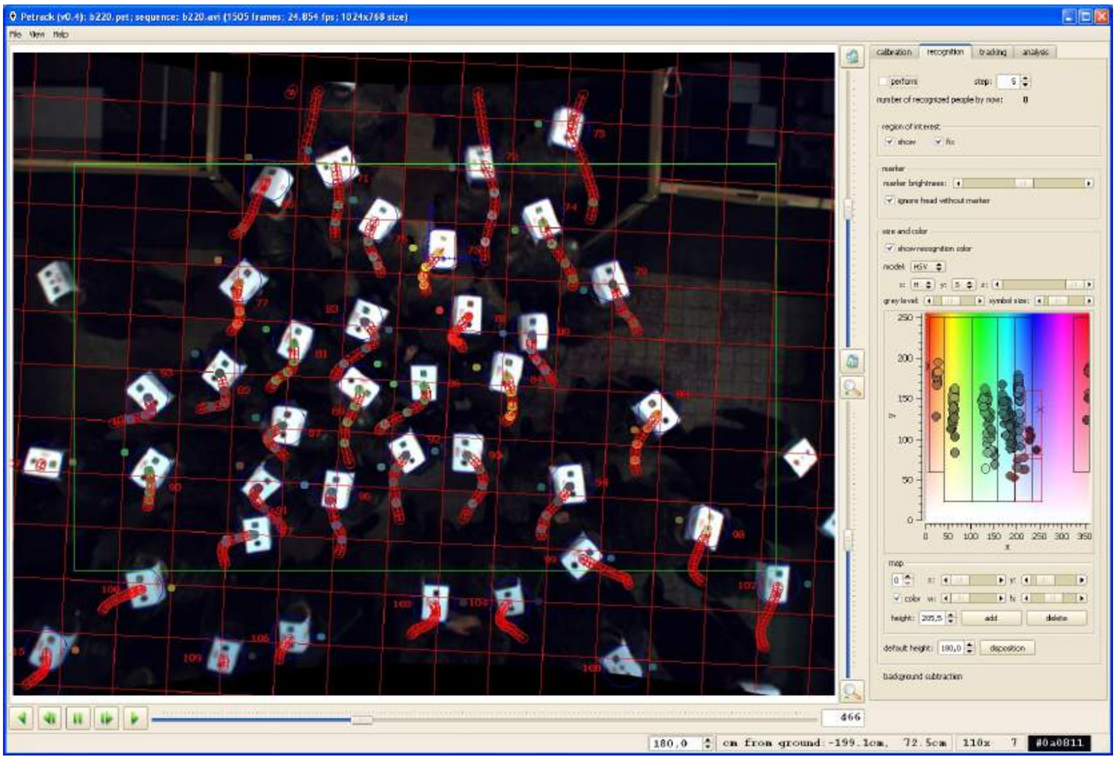


FIGURE 3.27: Head marker cap used under the lab settings experiments only.

- Provides measurements of objects on the computer screen such as icons, windows and images.
- Provides measurements using numerous units. These units can include pixels, points, twips, centimetres, or user-defined measurements.
- For external processing or later playback measurements can be recorded to an XML file.
- For implementing accurate measurements it calibrates screen resolution.
- Arbitrary portions of the screen can be captured.
- The screen can be magnified up to 32 times magnification.
- Rulers can be displayed anywhere on the screen.
- A grid overlay can be displayed with adjustable grid spacing on the screen.

If the measurement is needed in pixels, then there is no need to calibrate the tool. However, if there is a need to perform measurements in other units (as required in this thesis) the tool should be calibrated. Internally all measurements are first carried out based on pixels and then converted to the desired unit using the screen resolution. The operating system reports a rough approximation of the screen resolution, and is unaware of the actual screen resolution which is dependent on aspects of the display screen that the operating system cannot access. Therefore, the operating system produces an inaccurate measurement value for the screen resolution on most display screens.

We used Meazure in this thesis to measure the travelling distance and speed of an agent from the images. The reason for using Meazure is because of the above mentioned features and for its capabilities to provide accurate measurements of any objects on the screen.

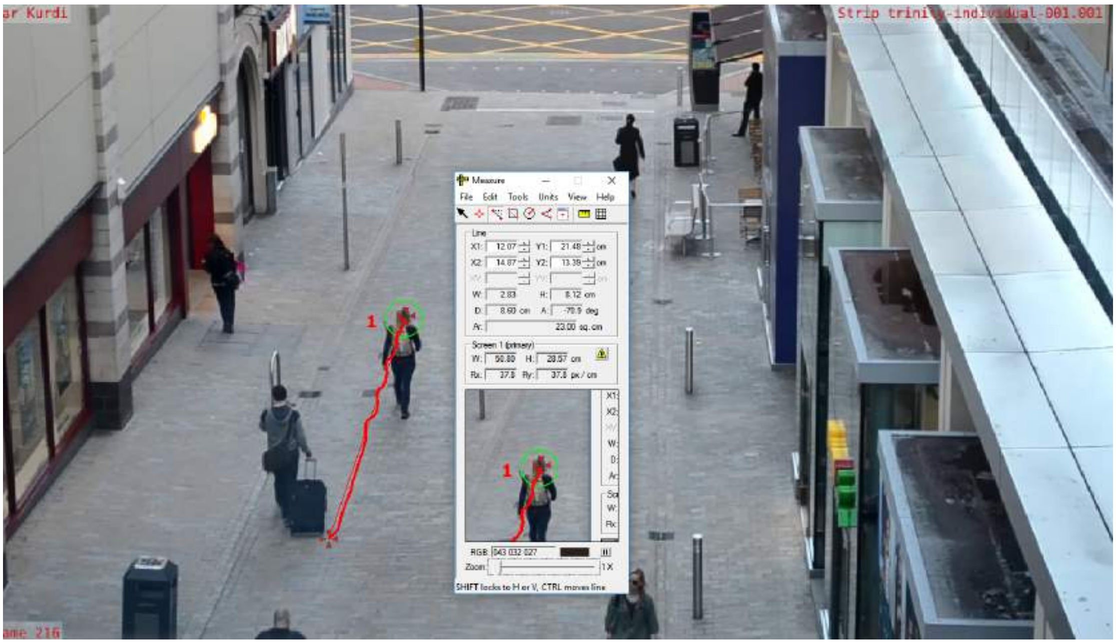


FIGURE 3.28: The Meazure's window shows its pointer while pointing the two ends of trajectory of individual walking in the Trinity mall.

The main window of the Meazure tool is shown in Figure 3.28. There are various sub-tools available as part of the Meazure tool to perform different measurements. Here we describe one of the sub-tools called *Line Tool*. The user can position two crosshairs using the line measurement tool anywhere on the screen to measure the positions, distance and other information for the line joining them. In addition, the angle of the line joining the points and the bounding rectangle can also be measured using the tool. Both the Meazure's tool information section and the data window attached to the crosshairs, display the measurement information. The pixel colour in the middle of the crosshair as well as the area surrounding the crosshair that is being changed, is shown by the magnifier window as shown in Figure 3.28.

The following measurements for the *Line Tool* are displayed by the tool information section:

- X_1, Y_1 - Point 1 crosshair's position
- X_2, Y_2 - Point 2 crosshair's position
- H, W - The height and width of the bounding rectangle for the line.
  $H = |Y2 - Y1| + 1$, $W = |X2 - X1| + 1$
- L - The length of the line joining the two crosshairs. $L = \sqrt{W^2 + H^2}$
- A - The angle of the line corresponding to the x-axis. Using the default coordinate system, positive angles are measured clockwise from the positive x-axis to the line from Point 1 to Point 2.
- A_r - The bounding rectangle's area for the line, $A_r = (W \text{ x } H)$

The computation of H, W, L and A_r is always implemented in pixel units and the obtained result is changed to the currently selected display units. An example screen with these measurements is shown in Figure 3.29.

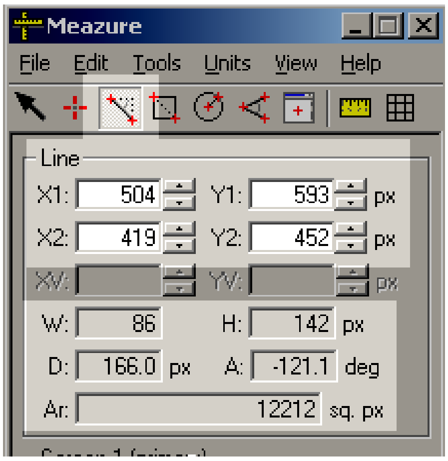


FIGURE 3.29: The Meazure tool information section window with the measurements.

3.11.5 MtPaint

MtPaint [130] is an open source software tool for creating pixel art and manipulating digital photos. The main task performed by MtPaint is Pixel Art. This technique is very elementary and complementary to painting in the real world. For example mtPaint provides a brush to paint with, a canvas to paint on, and a palette of colours for the brush to use. The main window of the MtPaint while building the corridor layout is shown in Figure 3.30.

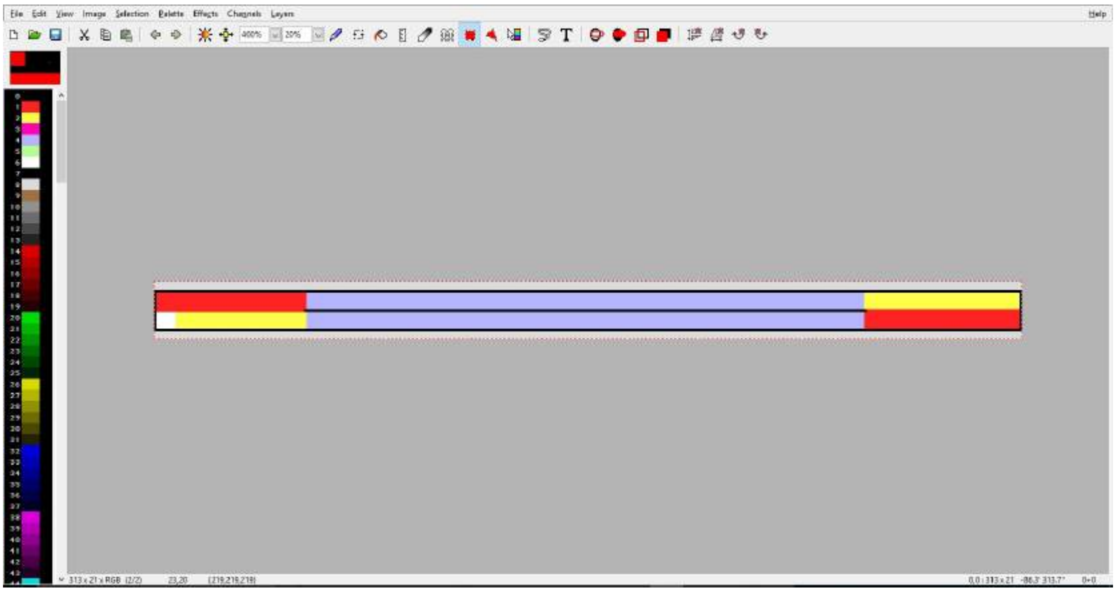


FIGURE 3.30: The main window of the MtPaint while building the corridor layout.

MtPaint is very similar to the windows painting tool and comes with lot of tools to accomplish similar tasks plus many more. We were mostly interested in the image manipulation tools. MtPaint has several general image manipulation facilities that are useful for various tasks such as; cropping, scaling, skewing, segmentation, resizing the canvas, adjusting the image gamma, brightness, contrast, saturation and hue, and various other effects. One interesting use of MtPaint is to extract an object from the image. For an example the reader is referred to [130].

3.11.6 FLAME

In section 2.3.3.5 we described it in details.

3.11.7 NetLogo

NetLogo [103] is a functional programming language which uses turtles (agents are called turtles in NetLogo) to represent agents, and comprising states such as unique identity, position, and user-defined attributes. The position of an agent in the space is represented by a patch (also called a cell). Each patch has a so-called patch-own variable that stores information, such as the size and visibility of the patch, etc, about the patch. This information helps compute the movement and density of the agents. The behaviour of an agent is modelled using Stream X-Machines [127].

A (stream) X-machine is an 8-tuple $\mathbb{X} = (\Sigma, \Gamma, Q, M, \Phi, F, q_0, m_0)$

where:

- Σ and Γ are input and output alphabets, respectively.
- Q is the finite set of states.
- M is the (possibly) infinite set called memory.
- Φ is a set of partial functions φ; every function maps a memory value and an input to an output and a possibly different memory value, φ:$\Sigma \times M \rightarrow \Gamma \times M$.
- F is the next state partial function, $F : Q \times \Phi \rightarrow Q$. This function when given a state and a function from the type Φ determines the next state. F is generally represented as a state transition diagram.
- q_0 and m_0 are the initial state and initial memory respectively.

In order to model the behaviour of an agent using X-machines, some of the mappings of the former to the latter are done as follows:

- Agent percepts form the input alphabet Σ, and are updated in each simulation cycle.
- Agents hold their simulation state (different that the X-machine State) and all parameters that affect their behaviour in memory M. For instance, agent gender and speed, can be modelled as elements of memory M.
- Agent behaviour is modelled as a set of functions Φ, and obviously the transition diagram F.
- Finally, agent movements are mapped to the output Γ. A delicate issue regarding modelling appears here. Since, according to the X-machine model, output cannot change the memory, actions should be implemented carefully, so that they do not change the X-machine state of the calling agent, but only the simulation environment.

3.11.7.1 TXstates Library

TXstates library [127] developed by Ilias Sakellariou, gives Netlogo developers the ability to model agent behaviours by using X-machine. The library enables X-Machine execution; it is specifically developed for NetLogo; allows for the ease of encoding transitions, states and functions; and there by producing the rapid development of X-Machine models. An interpreter executes agent specifications while respecting the semantics of X-Machine, which hereto allows for the easy assembly of simulations.

TXstates provides support for easily encoding states as follows.

- Memory M is a NetLogo table and is stored in a turtle-own variable. Each agent (turtle in NetLogo) must carry its own state and memory information. To do so, TXstates requires a number of agent own (turtle-own) variables to be defined in the NetLogo model. The turtle-own variable is initialized and the memory is created by the TXstates' commands *x-init-memory* and *x-mem-initial-var* <*varName*> <*Value*>, respectively. *x-init-memory* initialises memory to an empty structure, and is required to be invoked only once. *x-mem-initial-var* <*varName*> <*Value*> adds a new X-machine variable value pair to the memory. The first argument <*varName*> is a string representing the name of the memory position and the second argument <*Value*> is its initial value.
- The set of states Q and the transition diagram F are encoded using the primitives of the TXStates. Information regarding a single state and the related transitions is encoded as:

```
state <StateName> \\
\# x-func <XMachineFunction 1> goto <StateName 1> \\
. . . . . . . . \\
\# x-func <XMachineFunction n> goto <StateName n> \\
end-state \\
```

where <XMachineFunction> is a NetLogo X Function of the special *type* and <StateName> is the name of the target state of the transition (a simple string). NetLogo X Functions have no arguments and operate on input and memory and produce output and memory updates. Thus, it is assumed that each function always has access to the former and produces output to the latter.

- Functions of the set Φ are encoded as NetLogo X Functions, that return results in a specific format, the latter being processed by the TXStates interpreter.
- The output Γ contains an action represented as NetLogo tasks and contains the (set of) NetLogo procedures, applied to the simulation environment by the interpreter. TXStates supports encoding such tasks as part of the X-machine function specification.
- Finally, input is provided by the simulation environment, through an appropriate turtle variable. TXStates provides appropriate primitives for encoding input management.

Executing the agent specifications presented above is the responsibility of the TXStates meta-interpreter. The latter is invoked by calling the *execute-state-machines* command, usually in each simulation cycle. Examples of TXstates scripts developed in this thesis are given in Chapter 5. More details about TXstates are provided in Section 3.11.7.1.

We summarize the advantages of NetLogo as follows. NetLogo platform is notably simplistic and suitable for prototyping, moreover it's capacity to establish automatic drawings of 2D or 3D agents as well as its ease of use makes it ideal for developing and simulating agent-based models. Several tools have been added to improve the visuals of NetLogo [131], that has made it a very good choice to visualise the simulation model directly. NetLogo in general provides an environment for the examination of structure formation, and delivers adequate approaches to batching runs over a parameter space. In addition, the number of example models, the user community, and the documentation available for NetLogo are excellent.

3.12 Correctness of Programming

the agents moving within groups try to stay with the leader and the group, the agents walking at a lower speed are overtaken by the agents walking at a higher speed; and how the safety (i.e. no accidents, such as stampedes, etc) of the pilgrims corresponds to the ritual performance either alone or in a group. We provide (in section (3.14)) program correctness of our *Sa'yee* model using code walk through, debugging, model logging and unit testing.

The *Sa'yee* model is written in Logo language using the NetLogo tool v.5.02 and consists of 4,500 lines of code. The steps taken to render programming correctness include performing tests, identifying errors, correcting the code, and then starting again with testing. In particular, several approaches were performed to recognize errors in the code.

We systematically walked through the program to verify that the code was written according to the design specifications, and was correctly matched with each algorithm. Each function was tested individually; then a group of related functions were also tested. An analytical and structured debugging was performed for test cases using the interactive and logging features of NetLogo tool. The key data for each agent was saved for every time step of the simulation, and was analysed and checked for agent behaviour and interaction with other agents. As part of the development process different prototypes were implemented, incrementally making each better than the previous one, leading us to the final implementation state of the *Sa'yee* model.[9]

3.13 Calibration

To calibrate the speed of the three types of agents, we need to set these values such that they match the real data. To accomplish this several simulations have been performed that involved pilgrims walking once through the corridor, i.e. agents entering the corridor at the *Safa* end at a consistent rate and vanishing when reaching the *Marwah* end. To calibrate the system model, two separate values of the entrance rate were taken into account that culminated in having roughly 400 and 500 agents in the corridor respectively. The average values of the agents' speed were measured by generating

[9] The *Say'ee* model code available on-line (https://goo.gl/GPBWkq)

a population of approximately 70000 agents. This process has resulted in the speed distributions shown in Table 3.6.

Table 3.6: Speed distributions (70000 agents)

	Mean speed (cells/tick)	**Deviation**	**Mean speed (m/sec)**	**Mean speed (km/h)**
Men	4.1	0.4	1.64	5.9
Women	3.7	0.4	1.48	5.33
Disabled	3.5	0.1	1.4	5.04

Each agent takes up an area (cell) of 40 by 40 cm. Table 3.6 shows the average speed in cells/tick (1 tick = 1 sec), m/sec and km/h; e.g. for men these values are 4.1, 1.64 and 5.9, respectively. The standard deviation for agent type is provided as well, resulting in the normal distribution of both the parameters for each agent type now being fixed. Mean speeds are slightly greater than the means presented in actual results (see Table 3.5). The reason for the higher speeds is because of the pedestrians going much faster than rest of the pedestrians.

Different number of experiments were carried out with 400 and 500 agents in a lane, running each of them four times with different random seeds. For each of the experiments we measured the average speed in km/h using the above mentioned normal distribution parameters as provided in Tables 3.7 and 3.8. The average speed was computed using a total of 70000 generated agents.

Table 3.7: Average speed values (in km/h) with 400 agents in the lane.

Experiment	**1**	**2**	**3**	**4**
Men	5.76	5.76	5.76	5.76
Women	5.2	5.19	5.19	5.19
Disabled	4.93	4.73	4.88	4.88

Table 3.8: Average speed values (in km/h) with 500 agents in the lane.

Experiment	**1**	**2**	**3**	**4**
Men	5.67	5.64	5.63	5.63
Women	5.13	5.11	5.11	5.09
Disabled	4.81	4.75	4.74	4.81

The average speed values in 3.7 are closer to the real values in Table 3.5, whereas those in Table 3.8 are lower than values in Table 3.7. This is considered normal as the pedestrian density is greater in the first case.

3.14 Validation

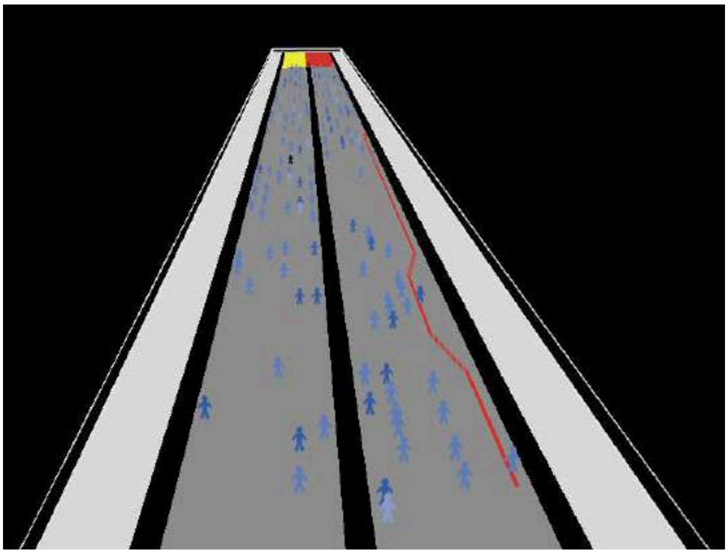
Validation may be described as a process of verifying, whereby the framework satisfies the necessary criteria and fulfils its suggested aims. When handling real data in mind of achieving model validation, there are problems in its completion, circumstances depending. In this case, the data gathered comprising videos, meaning there is the need to establish some statistical data relevant to the simulation in order to establish validation.

Accordingly, throughout the validation process, the patterns observed in videos that may be emulated in simulations in particular controlled conditions provide the restricting guidelines. Firstly, we review the density of the agent population at different corridor locations. The videos provide insight into the density at both corridor ends, which is greater than at any other point in the corridor. This attribute needs to be verified, as a goal, which is one aspect of the simulation. Face validity seeks to establish whether or not the framework acts reasonably and makes subjective judgements in terms of whether or not the model may be considered accurate[4]. The professionals in this regard can provide judgement as to its accuracy through the following considerations:

- Animation: this provides a graphical representation concerning the model's behaviour over time. Various simulation software, including Swarm and Repast, have incorporated features geared towards animation and may even track the properties of the individual when the simulation is functioning.
- Graphical Representation provides an overview of the model's output data (comprising mean, distribution, and a variable's particular time series) with the use of different graphs. Such graphs may be useful in making subjective judgements.

Model developers further utilise Animation and Graphical Representation when seeking to achieve code verification in the framework application process. Face validity is recognised as being the first stage in a three-stage method created by Naylor and Finger [132]: insert ref and widely followed in industrial and systems engineering[4]. Throughout this

(A) Overtaking (actul video trace)

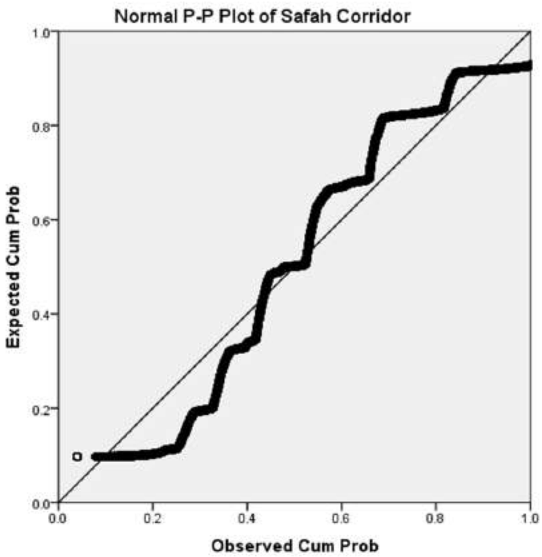


(B) Overtaking (simulation trace)

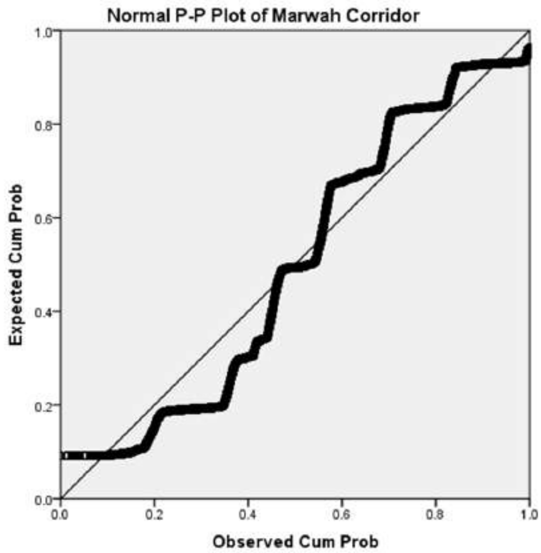
FIGURE 3.31: Face validity comparing overtaking of pedestrians between real video footage and simulation.

experiment, the validity of the framework is achieved, with the results provided for the purpose of analysis. Face validation see experiments ...

Models are neither perfect nor 100% error free, and cannot claim that they fully match the real system. The real data collected in this thesis consists of videos, and therefore as part of the model validation process we use simulations to reproduce patterns observed in these videos. An empirical study (experiments) has been carried out to show that some aspects of the model match the real *Sa'yee* crowd behaviour, like: the agent population



(A) Safah corridor P-P Plot analysis



(B) Marwah corridor P-P Plot analysis

density which is higher at either end of the corridor than in the rest;

We conducted a various number of experiments. Pilgrims performed the ritual alone (not in groups) during the first class of experiments, entering the corridor at a rate of five agents per second through the area marked as *Entrance* (Figure 3.21). Throughout all experiments the agent density was measured at either end of the corridor, as shown in Figure 3.21. In our simulation model, when the corridor is at population of 500 agents the average density value is almost the same at either end and throughout the corridor, and has a value between 1 and 2 when the system is stable, which occurs after approximately 100 simulation steps. Whereas, when the corridor is at a maximum population of 1500 agents the average density value is between 5 and 6 at either end of the corridor, and is between 4 and 5 throughout the rest of the corridor after approximately 250 simulation steps.

3.14.1 Statistical Validation FLAME and Netlogo

The statistics obtained from the two models is validated using a PP (probability-probability) plot. In this plot, the distribution of data obtained from two models is compared against a 45 degree theoretical distribution line. In the p-p plot of *Safa* corridor and *Marwah* corridor, the data plot follows the theoretical line with a very little variance. This suggests that data from the netLogo and Flame simulations are similar and there is no significant variance.

Chapter 4

Results and Analysis

4.1 Introduction

In this chapter we present six groups of experiments have been done in this research and their results with interpretation of them:

- Speed distribution experiments to calibrate model speed.
- Agent density manipulation to reproduce the observed behaviours on real videos such as the density at the both end of the corridor much higher than the rest these experiments have been done in three classes the first class agents entering from entrance and in the second class of experiments agents randomly placed in the corridor third class allotment of agents in groups meets the the collected data distribution.
- Agents behaviour to the groups;
- Agents safety by testing the effects of the group size on the *Sa'yee*;
- Disabled safety by dedicate the corridor for disabled only this are done by running the simulation with one type only of agents (disabled) 6 times with population of 1000 agents to 6000 agents then the results were compared with mixed ratio population;
- Effect of entry rate on the time of completion the ritual.
- Finally we presenting the results of FLAME model execution time Vs Netlogo at different population size 1000,2000,...,6000 agents respectively to compare the execution speed of them.

4.2 Experiments of Agent density

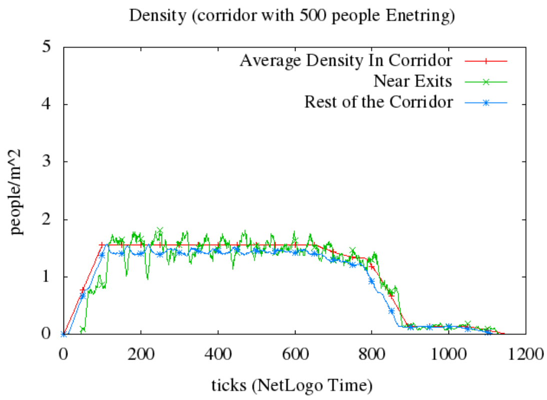
The first feature we considered in this experiment is density of the agents population at different points of the corridor. As noted in the videos, the density at either of the two ends is higher than in the rest of the corridor. We want to verify this pattern in the videos by simulating the model. As part of this process multiple sets of experiments have been conducted, based on the pilgrims performing the ritual alone or in groups.

4.2.1 Entering to Empty Corridor

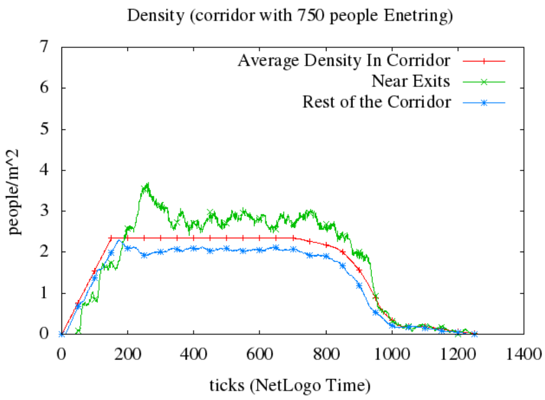
In this class of experiments, the pilgrims were performing the ritual at a rate of 5 pilgrims per second and entering the corridor alone(no groups). Pilgrims that entered the corridor (using the area labelled as the *Entrance*) were allowed to finish the ritual, i.e. seven revolutions in the corridor. The population generated was 5% women, 94% men and 1% disabled. Experiments were conducted with a maximum population in the range of 500 – 1500 agents in the corridor, in steps of 250 agents. In the experiments the density of pilgrims was measured at either end of the corridor, as well as in the rest of the corridor. The areas at the end were approximately 24 square meters.

4.2.1.1 Results

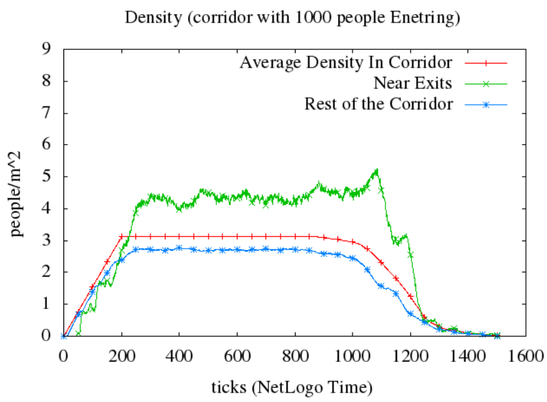
The experiments showed that the agent density in the corridor goes on increasing up to a level and reaches the maximum agent density and hovers around that maximum density for 200 ticks to 800 ticks for 500 people entering the corridor For the same configuration of the experiment, the average density of agents near the exits and rest of the corridor show a similar graph which increases up to approximately 1.5 people per meter square up to the nearly 150 ticks and then fluctuates around that same agent density up to 800 ticks and then finally decreases to reach the base line at around 1200 ticks. The graph further shows that the fluctuation in the agent density near the exits is higher than the fluctuations of average agent densities and the agent density of rest of the corridor. For the experiment consisting 750 agents, the average density shows the maximum value a bit higher than 2 people per meter square. It further shows that the agent density near the exits have increased considerably to a value nearing 4 people per meter square. The agent density keeps on increasing up to around 200 ticks and



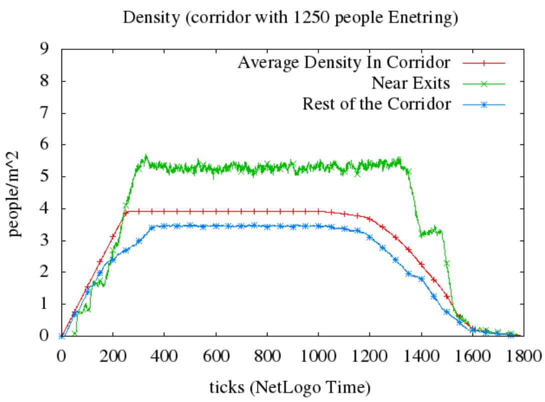
(A) 500 agents entering



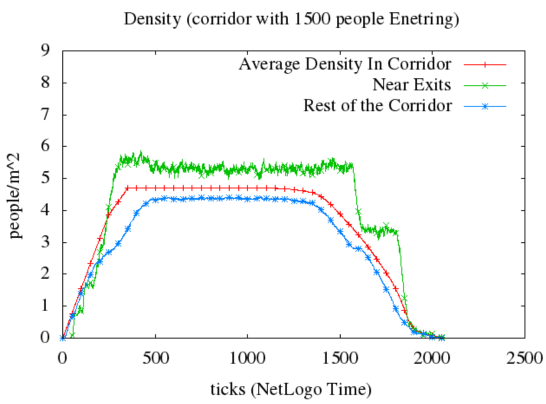
(B) 750 agents entering



(C) 1000 agents entering



(D) 1250 agents entering



(E) 1500 agents entering

FIGURE 4.1: Density Values Where Agents are Entering the Corridor.

the graph starts declining form around 900 ticks and finally reaching 0 agent density just beyond 1200 ticks. The third class of experiment for 1000 agents shows further increase in the average agent density in the corridor of nearly 3 agents per square meter. This experiment suggests more increase in the agent density at the exits reaching the maximum agent density up to nearly 6 agents in around 1100 ticks.The agent densities for the average, near the exit and rest of the corridor shows very less fluctuation in the agent densities between the range of 200 ticks to 1200 ticks. For the experiment using 1250 agents the average agent density has increased up to 4 agents per square meter, and the maximum agent density for near exits is seen to hover around 6 agents per square meter. The maximum agent density for rest of the corridor lingers just below 4 agents per square meter. The graph further suggests that the agent density keeps on increasing up to 300 ticks and fluctuating around that range for around 1400 clicks and reaching 0 square per meter square at around 1800 ticks. If we take 1500 agents in the modelling then we see similar results as that of 1250 agents entering with more or less similar value for the maximum agent density for near exits. The average density for the rest of the corridor increases unto around 4 agents per square meter and average density in the corridor is found to fluctuate around 5 agents per square meter. The agent density keeps on increasing from 400 ticks and starts decreasing from 1700 ticks ultimately reaching 0 at around 2000 ticks. The graphs obtained from the experiment suggest that with the increase in the number of agents the agent density keeps on increasing up to a level and then maintains a constant agent density. The decrease in the the density after certain ticks can be explained as the decrease in number of agents at the end of the simulation; meaning that in the real life scenarios the agent density will remain more or less constant throughout the whole ritual.

4.2.1.2 Agents Density Experiment's Results Interpretation

The experiments where we introduced agents on the empty corridor showed initial sharp increase in the agent density, whether it be near the exit or in the corridor or the average agent density. This sharp increase can be explained as the sudden build up in the congestion of people first in the entry gates, then in the corridor and the whole density contributing to the average agent density of the corridor. In the middle of the experiments the agent densities remain more or less constant, it is because the individual agents do not often stop in the middle of the ritual or block passage to other agents.In the final section of the modelling the agent density seem to decrease in a periodic manner, this can be accounted for the decrease in the number of agents as the determined number of agents have already passed the corridor and less number of agents means less congestion in the exit, corridor and the average as a whole.

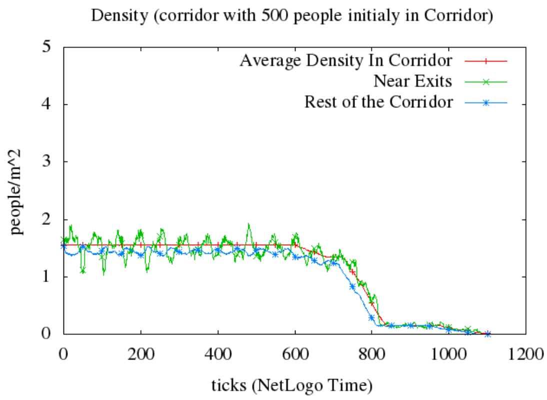
General individual behaviour while doing a collective behaviour is following the one just in front of us. Meaning that in the *Sa'yee* ritual the pilgrims walk in a constant speed whenever the corridor is void of any groups, just following the one directly in front of them. This will give constant crowd speed and maximum saturated agent density whenever no groups are present. So, it can be suggested that the congestion level and chances of stampedes or mishaps decreases whenever only single individual are entering through the corridor.

4.2.2 Randomly Placed in the Corridor

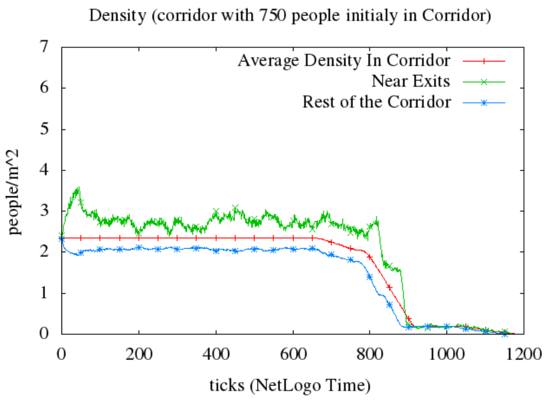
In this class of experiments, the pilgrims were also performing the ritual alone. They were initially placed in random locations within the corridor, and were then also allowed to perform seven cycles as in the previous experiments. We conducted experiments with a maximum population in the range of 500 – 1500 agents in the corridor, in steps of 250 agents. We measured densities at both ends of the corridor. As observed in Figure 4.2 density follows a similar pattern, although it rapidly reaches an *equilibrium* state. The latter is defined as having both ends of the corridor congested, and is demonstrated by consistently having a higher density of agents in the ends of the corridor.

4.2.2.1 Results

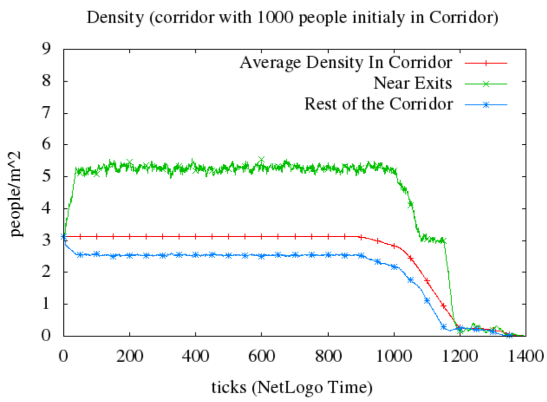
In the first configuration of the experiment, 500 agents were modelled such that they were already present in the corridor which showed that the maximum agent density near the corridor, the exits and the average agent density just remained below 2 agents per meter square. Since the agents are already present in the corridor the maximum agent density starts below 2 which then starts falling after around 700 ticks reaching 0 agents per meter square at below 1200 ticks. For the second configuration of the experiment we introduced 750 agents in the who were initially present in the corridor. Doing so the maximum agent density reaches just below 4 agents per meter square near the exits at the beginning in around 100 ticks and then decreases progressively to reach near 3 agents per meter square. The agent density decreases from 800 ticks and finally reaches to 0 at about 1200 ticks. The average density and the density in the corridor just fluctuates just above 2 agents per metre square from the range of the start to 800 ticks and then ultimately decreases to 0 at just below 1200 ticks. In the third configuration



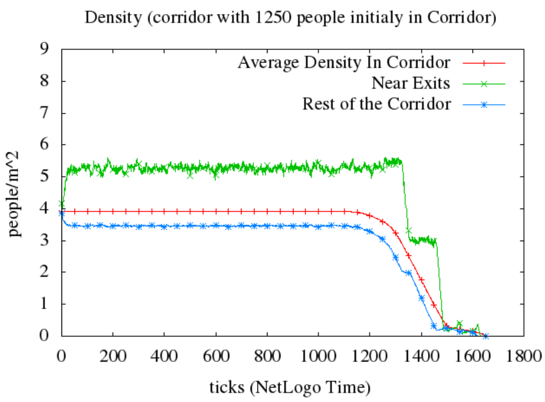
(A) 500 agents in the corridor



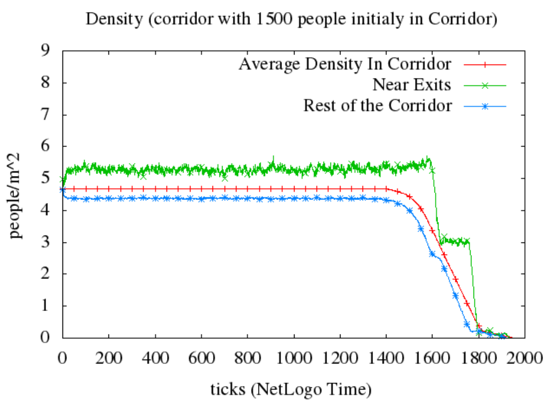
(B) 750 agents in the corridor



(C) 1000 agents in the corridor



(D) 1250 agents in the corridor



(E) 1500 agents in the corridor

FIGURE 4.2: Density Values Where Agents are Already in the Corridor.

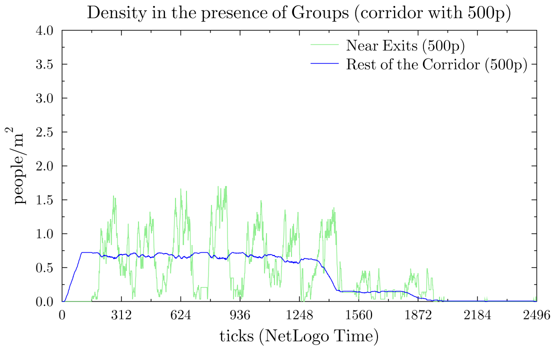
of the experiment 1000 agents were already present in the corridor which showed that the maximum agent density in the exits reaches up to above 5 agents per metre square. The density of corridor just remains below 3 agents per metre square and the average agent density remains just above 3 agents per metre square. The agent density kicks off with the maximum value and then starts decreasing at around 1000 ticks and finally reaching to 0 at about 1400 ticks. In the fourth configuration of the experiment 1250 agents were already present in the corridor. The experiment pointed out that the agent density in the exit reaches up to just below 6 agents per metre square with the agent density in rest of the corridor reaching up to above 3 agents per metre square and the average density up to 4 agents per metre square. The agent densities kick off with maximum values and then start decreasing at around 1400 ticks and finally reaching to 0 above 1600 ticks. For the fifth configuration of the experiment 1500 agents were already present in the corridor. Doing so the agent density near the exit reached above 5 agents per metre square. The average agent density and the agent density of rest of the corridor also increased considerably in this configuration reaching nearly up to 5 agents per metre square. The average agent density and the density of the rest of the corridor also increases to above 4 agents in this configuration.

4.2.3 Walking in Groups

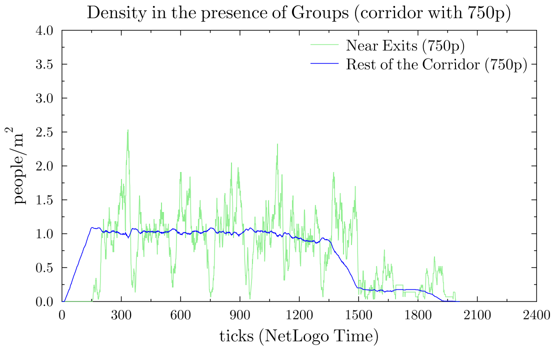
In this class of experiments, the pilgrims were performing the ritual in groups. Allotment of pilgrims to groups, pursued a distribution that was measured using actual data collected. The data indicated that 46% of the pilgrims were individuals, 36% couples, 6% were comprised of groups of three, 6% were comprised of groups of four and finally 6% were comprised of groups of five agents. Given the previous group attributes the simulation again generated pilgrims at a rate of 5 pilgrims per second, as individuals or in groups, and the greatest number of agents was in the same range as in the previous class of experiments. We conducted experiments with a maximum population in the range of 500 - 1500 agents in the corridor, in steps of 250 agents. Results of these experiments are shown in 4.3. The difference in the results of the experiments when the pilgrims are performing the ritual in groups, than the other two classes of experiments, is that the density i.e. agents/m2, does not stay constant near exits. This shows that agents while performing the ritual in groups wait for the leader and tend to stay in groups. Also for this class of experiments, as the number of agents in the corridor are increased the time to complete the ritual also increased for some of the agents.

4.2.3.1 Results

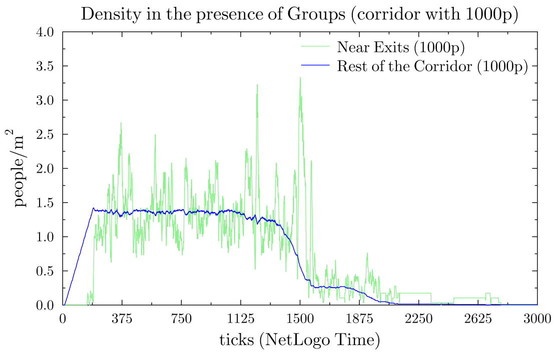
For the first configuration of experiment 500 agents were introduced which consisted of group of agents as well as individual agents. Doing so the agent density near the exit



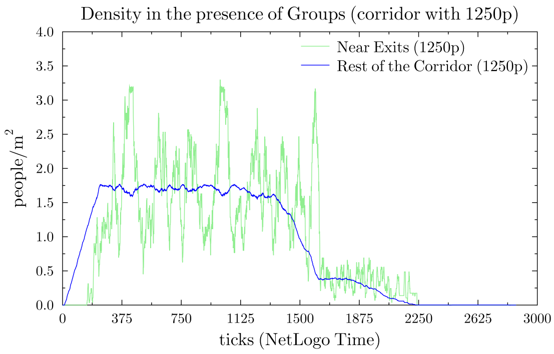
(A) 500 agents in the corridor



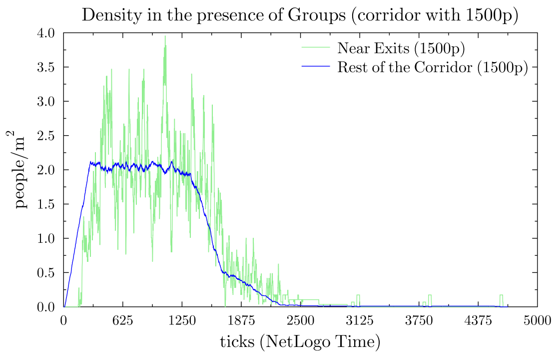
(B) 750 agents in the corridor



(C) 1000 agents in the corridor



(D) 1250 agents in the corridor



(E) 1500 agents in the corridor

FIGURE 4.3: Density Values in the Presence of Groups.

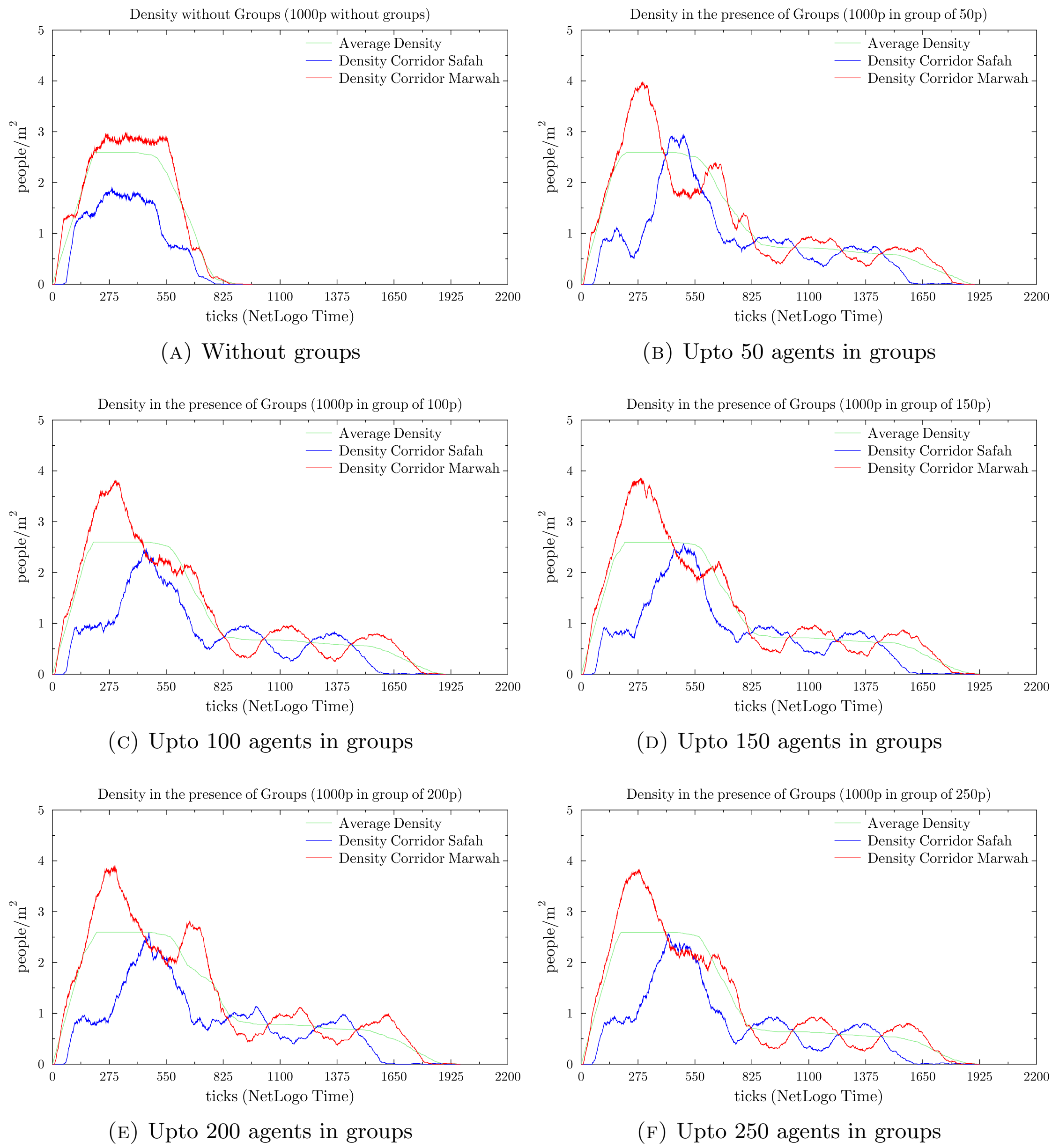
showed high fluctuation reaching the maximum value of nearly 1.5 agents per metre square and minimum of 0 agents per metre square. The agent density of rest of the corridor remained more or less around 0.75 agents per metre square. The agent density progressively decreased beyond 1200 ticks and finally reaching to 0 beyond 1800 ticks. The second configuration of the experiment consisted of 750 agents along with groups in them. Doing so more fluctuation was introduced in the agent density reaching the maximum value of 2.5 agents per metre square. the average agent density in the corridor remained nearly constant at the level of 1 agents per metre square. The started decreasing after 1500 ticks reaching to the minimum 0 agents per metre square at nearly

2000 ticks. The third configuration of the experiment introduced 1000 agents along with groups in them. Doing so the agent density in the exits peaked up to nearly 3.5 agents per metre square. Here also we see huge fluctuations in the agent density in the exits but the agent density in the rest of the corridor maintains nearly constant value of nearly 1.5 agents per metre square. The agent densities decreases progressively beyond 1500 ticks and reaching to minimum of 0 at around 2000 ticks. For the fourth configuration 1250 agents along with groups were introduced in the experiment. Doing so we found out similar result as that for 1000 agents with similar maximum agent density of 3.5 agent per metre square for the exit. Further we see that the agent density of the rest of the corridor also increases to about 2 agents per metre square as compared to 1.5 agents per metre square in the previous configuration. The agent densities keeps on decreasing form beyond 1500 ticks to reach the minimum value of 0 agents per metre square at about 2250 ticks. The fifth configuration of the experiment introduced 1500 agents along with groups in it. It showed that the agent density increases up to 4 agents per metre square in the exits and up to above 2 agents per metre square in the rest of the corridor. The agent density decreases after 1500 ticks and decreases sharply after 1600 ticks in ultimately reaching the minimum density at about 2250 ticks.

The agent density increases and decreases sharply when groups are introduced in the experiments. The graph shows sharp valleys and peaks showing sadden change in densities. Further the agent density in the exit start building up only after 150 clicks, it can be attributed to the logic that the exits are blocked as soon as the agents are introduced in the modelling.

4.2.4 Extreme Group Size

The third feature we considered is the safety of the pilgrims. We wanted to test our model against extreme cases (parameters) and check how these parameters affect the safety of the pilgrims. Safety here means, the ritual is completed without any accidents, such as stampedes etc. The extreme cases we considered were, agents performing the ritual in different sizes (0 – 250) of groups. For testing the safety we introduced 1000 agents in different settings. First without any groups, second people in group of 50, third people in the group of 100, fourth people in the group of 150, fifth people in the group of 200 and in the sixth configuration groups consisted of 250 people in one group.



(A) Without groups

(B) Upto 50 agents in groups

(C) Upto 100 agents in groups

(D) Upto 150 agents in groups

(E) Upto 200 agents in groups

(F) Upto 250 agents in groups

FIGURE 4.4: Experiments with and without groups, showing the density of the pilgrims (people) in the two corridors, for predicting safety of pilgrims.

4.2.4.1 Results

In the first configuration to test safety of the agents, no groups of agents were introduced. The graph shows similar characteristic as the graph of 1000 people entering. In the second configuration, people were divided into groups of 50 people. The graph shows that there is a sudden increase in the agent density as soon as the groups are introduced. The maximum agent density for the *Marwah* quickly reaches up to 4 agents per metre square and the maximum agent density for the *Safa* corridor reaches up to 3 agents per metre square. Then there is a periodic increase and decrease in the agent density which finally reaches to the minimum value of 0 agents per metre square at about 1800 ticks for *Marwah* and about 1600 for *Safa*. The average density also changes according to the changes in the density of the *Marwah* and *Safa* with a maximum agent density value of around 2.5 agents per metre square. In the other configurations as well we see similar results in the fluctuation of agent density of the people in *Marwah* and *Safa*. The trend of fluctuation is followed by the average agent density of the corridor as well.

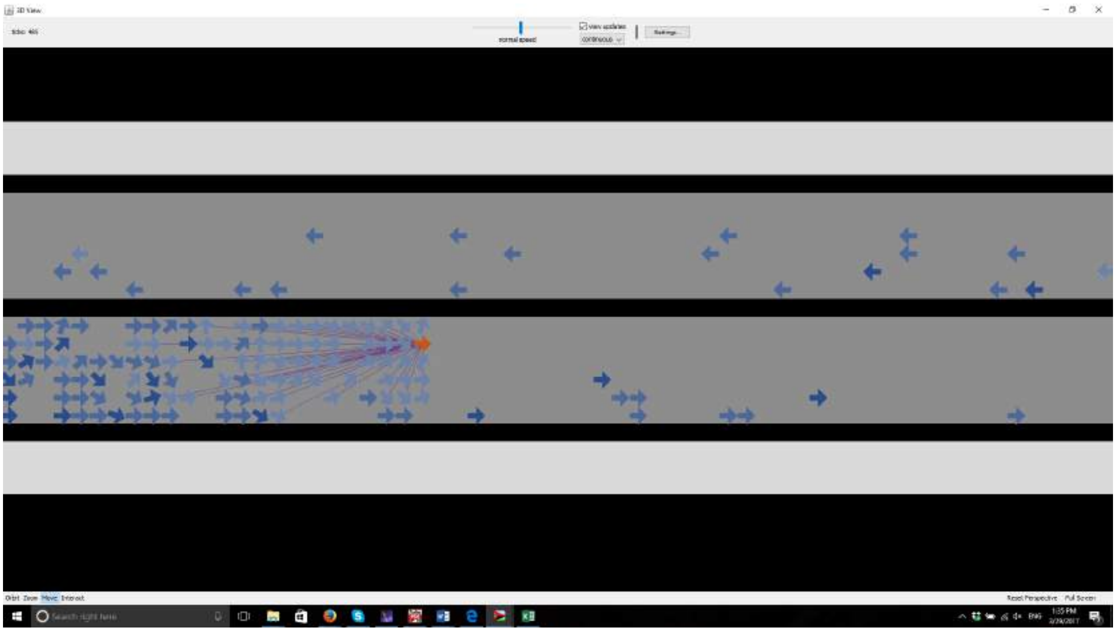
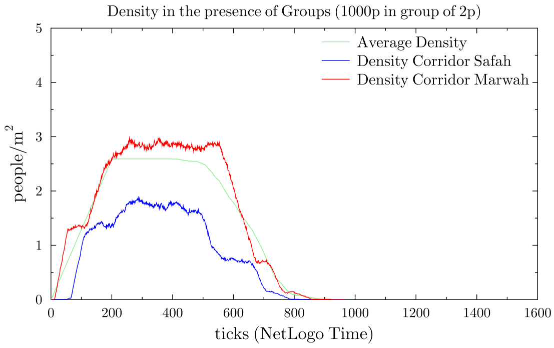


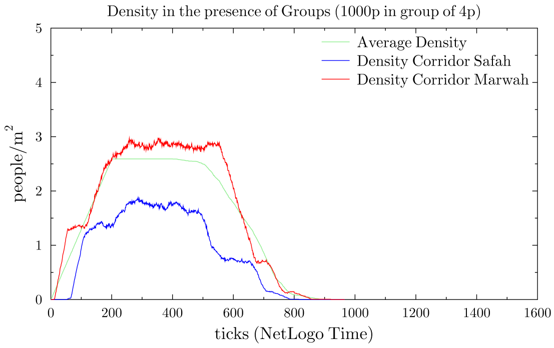
FIGURE 4.5: Screen shot of social crowd model shows large group blocking the corridor.

4.2.5 Optimal Group Size

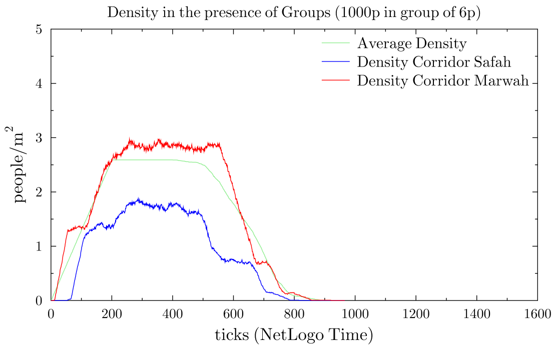
It is the general tendency of pilgrims to stay in groups for various reasons, such as the care of family members etc. Therefore, there is a need to find out what is the minimum safe group size. It is impossible to find an optimal value, of a group size, for safety of the pilgrims. We still wanted to provide a general rule for such purposes, and we carried out more experiments with group sizes ranging from 2, 4, 6, and 10 agents. Results of these experiments are shown in Figure 4.6. Also, we connected experiments decomposing large group to smaller groups. We took a group of 50 members and split it two times. first to 10 groups of size 5 persons. Second, to 25 groups of couples. Then compared the crowd performance in all cases as seen in Figure 4.7, as a general rule we can say that, smaller group sizes (less than 10) are safer.



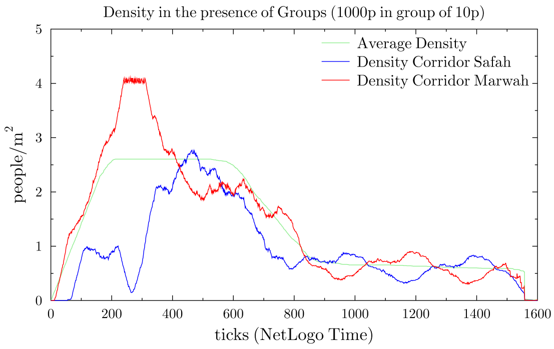
(A) Upto 2 agents in groups



(B) Upto 4 agents in groups



(C) Upto 6 agents in groups



(D) Upto 10 agents in groups

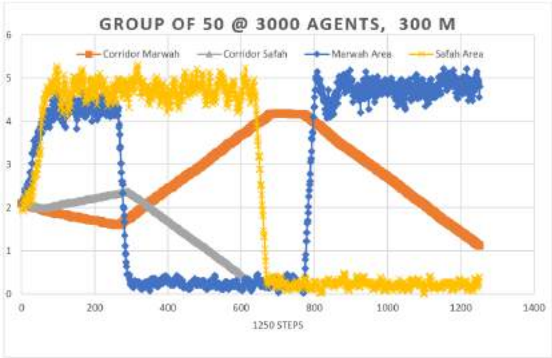
FIGURE 4.6: Experiments with groups for predicting an optimum value of a group size for safety of pilgrims.

4.2.5.1 Results

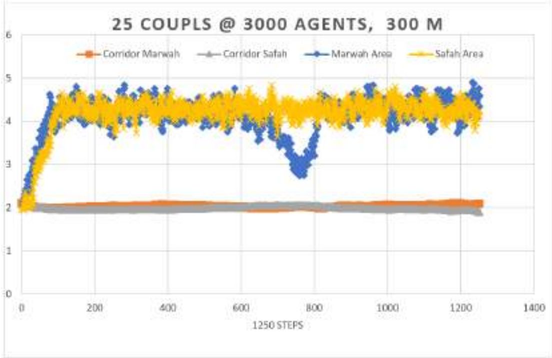
Whenever we split the groups into smaller sizes we observe that the groups with agents less than 10 people in the group has maximum agent density of around 3 agent per metre square. After the group size increases above 10 people in the group; the maximum agent density goes above 4 agents per metre square. Further we see periodic fluctation in the agent density of group consisting 10 people. This can be attributed to the periodic stopping of the groups in the middle and the sudden changes in the behaviour of the leader of the group. Thus setting 3 agents per metre square as the threshold for safety of people then we can conclude that the safety of pilgrims can be achived by defining group sizes that are less than 10 people in size.

4.2.5.2 Interpretation of Experiments of Groups

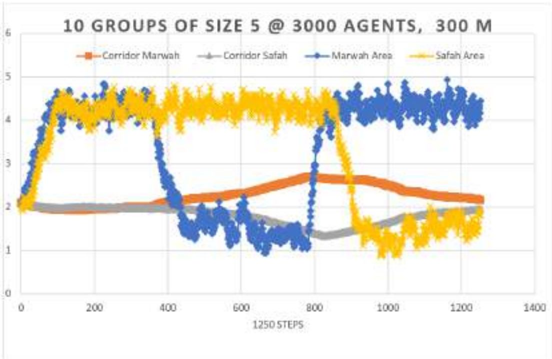
We conducted experiments with a maximum population of 1000 agents in the corridor, with a range of group sizes from 0 (without groups) – 250 in steps of 50 agents. The density of pilgrims correlates to safety of the pilgrims. For example a stampede which



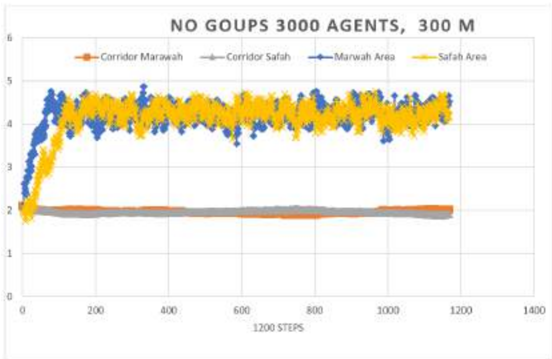
(A) Group of 50 agents in the corridor



(B) Group of 50 divided to 25 Couples



(C) 10 groups of 5 agents in the corridor



(D) No group

FIGURE 4.7: Experiments with groups to study the effects of decomposing large group to smaller groups.

can be recognised by the formation of a region of very high population density. These experiments show densities of the pilgrims in the two corridors. Results of these experiments are shown in Figure 4.4. As shown in Figures 4.4(b) – (f) when there are up to 50 – 250 agents in groups the density in the two corridors, except some of the times, almost remains the same. This density initially exceeded 2 and 3 agents $/m^2$ in the corridors of *Safa* and *Marwah* respectively, and latter settled down to 1 agent/m^2 in both the corridors. It also took much longer to complete the ritual in these groups. Whereas, as shown in Figure 4.4(a), the ritual is completed much earlier and with less congestion, i.e. a density less than 2 – 3 agents/m^2 in both the corridors, when the pilgrims are not in groups. Based on these results we can say that pilgrims are much safer in the corridors performing the ritual without groups.

It is the general tendency of pilgrims to stay in groups for various reasons, such as the care of family members etc. Therefore, there is a need to find out what is the minimum safe group size. It is impossible to find an optimal value, of a group size, for safety of the pilgrims. We still wanted to find a general rule for such purposes, and we carried out more experiments with group sizes ranging from 2, 4, 6, and 10 agents. Results of these experiments are shown in Figure 4.6. As shown in the Figure, as a general rule we can say that, smaller group sizes (less than 10) are safer. We used only a population of 1000 pilgrims.

4.2.6 Disabled Optimal Flow

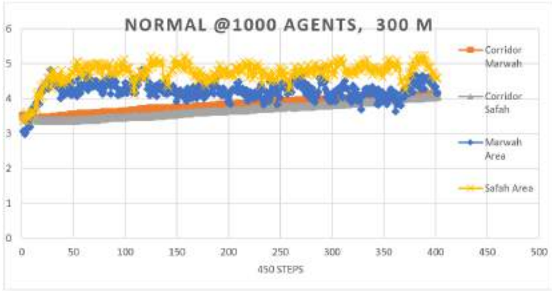
In this experiment, six individual experiments were carried out with the aim of garnering insight into the optimal management of the disabled flow in the corridor. Although it is not possible to accurately determine this through the completion of experiments,

we still garner insight into the situation through considering their speed. Following, the situation in terms of the dedication of this corridor for disabled persons only was considered. A total of 6 different populations were examined, ranging in size from 1,000 disabled agents to 6,000, in steps of 1,000 agents. Subsequently, a comparison was drawn between the results with the normal observed population situation, equal to 5% women, 94% men and 1% disabled, with the link between physical elements sought to be established. Subsequently, the aim focused on garnering insight into the decreasing pattern of a flow coefficient in contrast to the able-bodied population.

4.2.6.1 Results

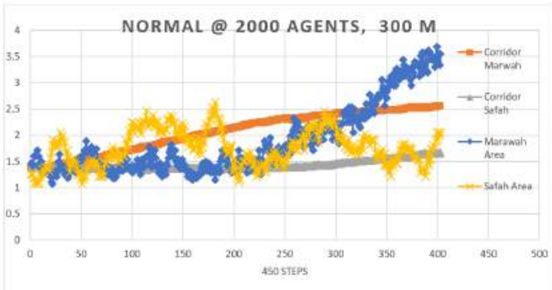
The graphs for disabled and normal people for 1000 agents show that the maximum agent density is above 5 agents per metre square for *Safa* area, below 5 agents per metre square for M*Marwah* area, about 4 agent per metre square for the *Safa* corridor and around 3 agent per metre square for *Marwah* corridor. The major difference in the graphs between the disabled people graph and the graph of normal people show a considerable decrease in the agent density of the *Marwah* corridor at the end of the ritual. In case of 2000 agents the graph for the disabled is a bit different from that of the normal people. The agent density of the *Safa* area keeps on increasing reaching up to 4 agents per metre square in maximum, but for the normal people the graph decreases at the end of the steps reaching up to only 2 agents per metre square. The comparison of the agent density in case of 3000 normal and disabled people show that the agent density in the *Safa* corridor and the *Marwah* corridor is considerably high up to the range of nearly 4 agents per metre square compared to the low agent density in the *Safa* and

(A) 1000 disabled only agents in the coridor

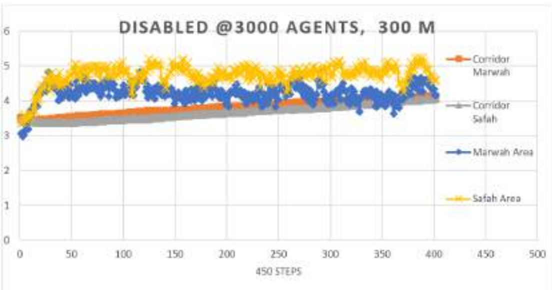


(B) 1000 normal agents in the coridor

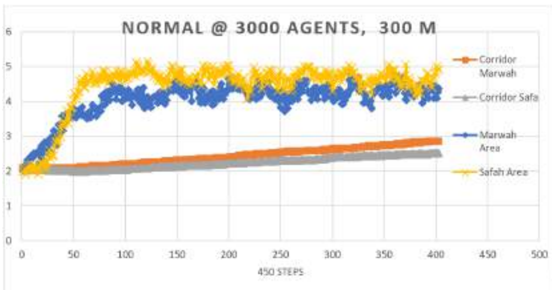
(C) 2000 disabled only agents in the coridor



(D) 2000 normal agents in the coridor



(E) 3000 disabled only agents in the coridor

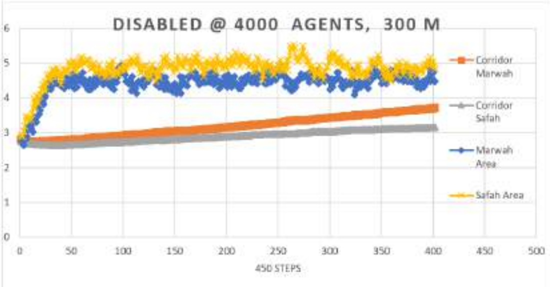


(F) 3000 normal agents in the coridor

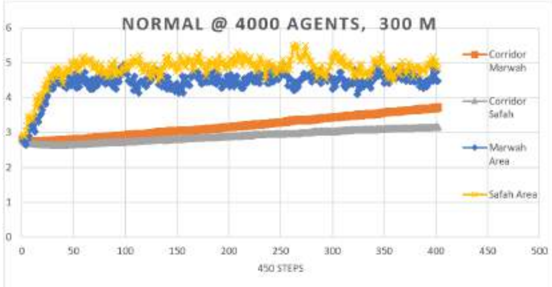
Figure 4.8: Density values comparison with disabled only Vs. normal population.

Marwah corridor which only reaches up to the density of 3 agents per metre square. On further increasing the number of agents to 4000, 5000, and 6000 we see similar results for both cases of 4000 with similar agent densities for disabled and normal person. But in case of 5000 agents we see that the agent density in the *Safa* and *Marwah* corridor is slightly higher for normal people compared to disabled person and in the case of 6000 agents the agent density for *Safa* corridor for normal people is a little higher than the agent density of disabled people.

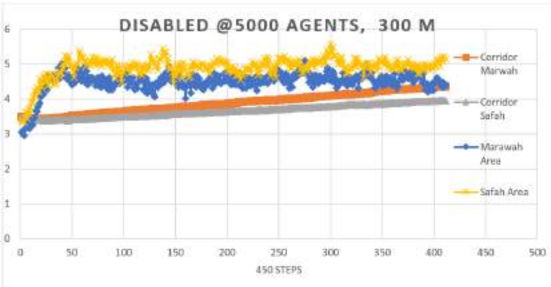
The speed of the normal agents and disabled agents in wheel chair is considered to be same in the modelling, but the difference in density for different number of agents can be accounted to the fact that the wheelchair occupy more space. Also if we take all



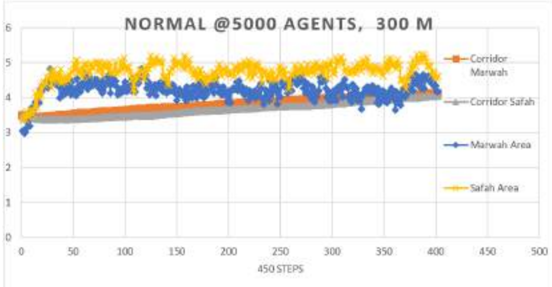
(A) 4000 disabled only agents in the coridor



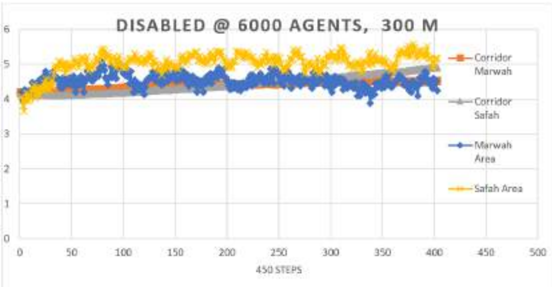
(B) 4000 normal agents in the coridor



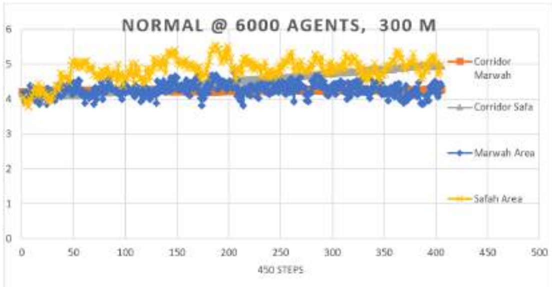
(C) 5000 disabled only agents in the coridor



(D) 5000 normal agents in the coridor



(E) 6000 disabled only agents in the coridor



(F) 6000 normal agents in the coridor

FIGURE 4.9: Density values comparison with disabled only Vs. normal population.

the agents to be disabled then the interaction between the wheelchairs can also increase congestion in the corridor.

4.3 Interpretation of Disabled Dedicated Lane Experiment

The experiments that were conducted with disabled agents only suggests that the crowd congestion will be low if we define a separate lane for the disabled people only. The graphs for disabled and normal people regarding different number of agents do not show significant differences except in some cases as in the cases of 1000, 2000, 3000, 5000, and 6000 agents. This can be explained as the walking speed of a normal human being is nearly same or comparable to the average speed of a disabled person in wheel chair. In the real life scene the ritual will be a huge mix of normal people, people in groups of different sizes, disabled people and so on. Hence the total interaction in unison will create agent density way too larger than the safer threshold. Hence the need for a different lane, that is completely dedicated to disabled people is justified.

The results and the plotted graphs suggest that the disabled only dedicated lane will have average agent density more similar to the results and graphs for normal people. So, it is better to separate different lane for disabled so that the crowd congestion comes under acceptable limit.

4.4 Experiment of Comparing FLAME and Netlogo

Six experiments have been made to compare the performance of models on running different population size. we started from 1000 agents to 6000 agents by steps of 1000 agents consecutively. FLAME shows superiority over Netlogo at the large scale crowd (see figure 4.10) while Netlogo perform better in the small scale up to 2000 agents. The graph between the execution time of simulation between Netlogo and FLAME tentatively shows that FLAME modelling is way too faster than Netlogo, but at the cost of programming complexity and development time. All the files required for simulation in FLAME should be ran in command line, which gives difficulty in programming and more complicated for debugging and checking. Also FLAME does not a include graphical tools so the user need to develop code for bolting results and visualise the simulation graphically. We choose to model our simulation in Netlogo as it is recommended for prototyping. Furthermore, agent based modelling for smaller number of agents such as the range of few thousand agent can be effectively done in Netlogo without any considerable lag in processing time.

4.5 Summary

We conducted an experimental evaluation of the simulated *Sa'yee* model using real data which were extracted from videos of the actual performance of the *Sa'yee* ritual. We also provided a detailed evaluation of the validity of the proposed model, and presented

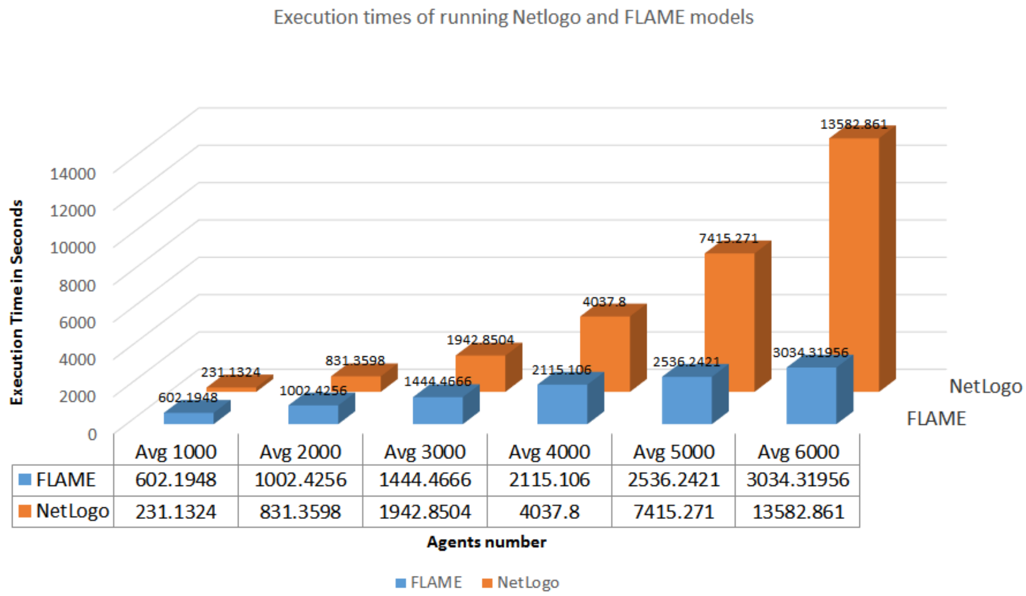


FIGURE 4.10: Comparison between FLAME and Netlogp execution times, shows superurity of FLAME on the large scale crowd.

results with discussions and analysis of this evaluation. During the simulation different populations of agents (pilgrims) were considered; single agents, groups, men, women and disabled.

We presented an empirical study consisted of multiple experiments, to validate the model's input, output, processes and agents behaviours and interactions. The study considered three features; agent density, behaviour and the safety of the *Sa'yee* model. The Study then matches these three features with the actual *Sa'yee* crowd depicted in the videos. We also provided program correctness through code walk through, debugging, model logging and unit testing. Based on the results of the empirical study we establish the following findings:

- The densities in the ends of the corridor are higher than those in the centre of the corridor.
- The agents walking at higher rate of speed will overtake those walking slower, and that the agents within groups prefer to stay within the group and with its leader.
- Pilgrims are much safer in the corridors performing the ritual without groups.
- For the pilgrims who stay in groups for various reasons, such as the care of family members etc., the smaller (less than 10) groups are safer than the larger groups.

Chapter 5

Conclusion and Suggested Future Work

Every year more than two million Muslims perform the Hajj pilgrimage in Saudi Arabia that includes a series of rituals. These rituals in the past have caused several tragedies due to congestion and stampedes. To avoid such tragedies there is a need to simulate crowd behaviour. This in turn will provide valuable information which will help improve the management of this important event, by smoothing out the crowd flow and varying the design compositions in areas where congestion occurs.

There are two important Hajj rituals *Tawaf* and *Sa'yee* that involve movements of large crowds. Many studies have been carried out to enhance the performance of these rituals. The techniques proposed in these studies focus mainly on crowd behaviours during the *Tawaf* ritual while very few focus on crowd behaviours during the *Sa'yee* ritual. In this thesis we have examined the management and enhancement of crowd behaviours in large gatherings, focusing specifically on the *Sa'yee* ritual. This ritual takes place within a corridor linking the two hills *Safa* and *Marwah*. Pilgrims are required to move between these two hills seven times. The *Sa'yee* ritual is a general case; that involves movements of large crowds; and can be applied to any crowded corridor [14]. These are some of the reasons for selecting this ritual as a case study for the thesis.

In the following sections we describe: a summary of the research contributions carried out in this thesis; some recommendations to enhance the performance of pilgrims during the *Sa'yee* ritual; limitations of the *Sa'yee* model and simulation results presented in this thesis; and some future works.

5.1 Summary of Contributions

- We have proposed, designed, and developed, a realistic and flexible state-based model of the *Sa'yee* ritual that mapped onto two different agent-based systems(Netlogo and FLAME).
- The model has been implemented on a multiple agent-based modelling (ABM) platform called NetLogo and FLAME.
- We have provided a evaluation and comparison of Netlogo and FLAME performance
- We have also proposed and developed a methodology to extract crowd characteristics from real-life videos.
- We have presented an empirical study to show that some aspects of the model such as agent density, behaviour, and safety match the real *Sa'yee* crowd. Therefore, the model can be used to enhance the performance of pilgrims during the *Sa'yee* ritual.
- We have provided a detailed evaluation of the validity of the proposed model, and presented results with discussions and analysis of this evaluation. The evaluation is based on real data extracted from videos of the ritual.
- There are two enhancements carried out in the *Sa'yee* model, and simulations that make this research novel and different than other such research. The first is the addition of disabled pilgrims, and the second is the use of the real video recordings to analyse and model the behaviours of the pilgrims.

5.2 Recommendations

Based on the model and the findings of the study carried out in this thesis we recommend the following general rules to enhance the performance of pilgrims during the *Sa'yee* ritual.

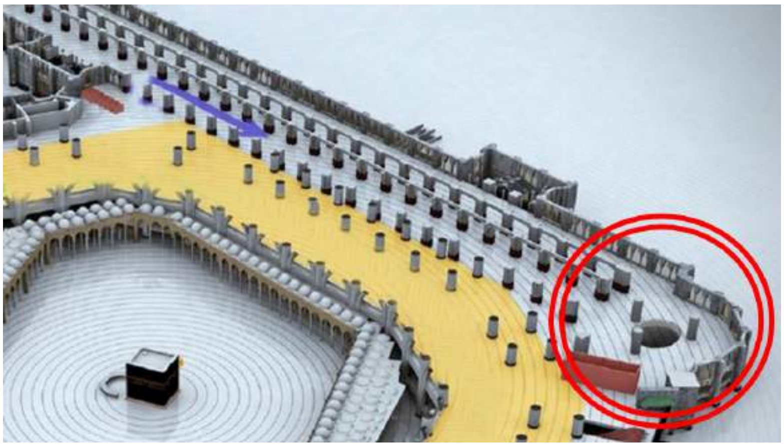


FIGURE 5.1: Depiction of the turning areas at the end of the *Sa'yee* corridor from *safa* side.

- During the study of the *Sa'yee* ritual we found that the density of the agent population is higher towards the two ends of the corridors than in the rest. Therefore, the ends of the corridor or the area closer to the exits should be made wider, to accommodate a larger number of pilgrims and also the turning of wheelchairs, compared to rest of the corridor. Figure 5.1 depicts the turning areas at either end of the corridor.

- During the study of the *Sa'yee* ritual we found that the agents walking at higher speeds overtake those walking at a lower speed. Therefore, there should be a separate lane marked with barriers for pilgrims who are disabled or walking at a slower pace, and education should be provided (in the form of electronic information signs or any slimier purpose devices) to pilgrims on how to take care of disabled, elderly, and weak people during the hajj rituals in order to avoid any accidents.

- It is the general tendency of pilgrims to stay in groups for various reasons, such as the care of family members etc. During the study of the *Sa'yee* ritual we found that when the *Sa'yee* ritual is preformed in larger groups the density of pilgrims/m^2 increases, and when the *Sa'yee* ritual is preformed in smaller groups the density of pilgrims/m^2 decreases. Therefore, in general smaller group sizes (less than 10) are safer than larger group sizes. The same should be communicated and taught to pilgrims through ,entry restriction rules to make their Hajj experience safer.

5.3 Limitations

In this Section we discuss some of the limitations of the model proposed, and the results presented in this thesis.

- The *Sa'yee* model proposed in this thesis is based on Agent based modelling (ABM). One issue related to the application of ABM is that the model has to be built at the right level of description, with just the right amount of detail to serve it's specific purpose. The model proposed in this thesis is only valid for the *Sa'yee* ritual and may not work for other Hajj rituals, such as *Tawaf* etc. In future we plan to research and explore, the possibility of designing and developing a general purpose model that works for both the *Sa'yee* and *Tawaf* rituals.
- Because of the limitations of the NetLogo framework we were not able to perform full-scale simulations and experiments. For example, we do not know how group sizes will effect the performance and safety in vary large gatherings (thousands/millions of pilgrims). With the availability of cheap computational power and new modelling frameworks like FLAME GPU it may be possible to carry out a full-scale simulation. In future, we plan to use FLAME GPU for modelling and simulations.
- One of the major issues with ABM is a practical issue and cannot be overlooked. ABM does not deal at the aggregate levels, but at the unit level. This issue is an advantage in one way by giving the modeller the ability to work at a very low (unit) level, however simulating the behaviour of all the units can involve extremely intensive computations and become very time consuming. Computing power is increasing, but modelling and simulating very large ABM systems still remains a problem. As mentioned above the FLAME GPU framework may solve some of these problems. We will however still need to look into other ways of using ABM to model and simulate very large systems such as the modelling of *Sa'yee* groups as one unit, etc.

5.4 Lessons Learnt

The modelling is based on the real time data taken from the video recording of the *Sa'yee* ritual. During the entire modelling process we used various tools and got through different concepts regarding Agent Based Modelling(ABM). The following are vital lessons that we learnt during the modelling:

- Agent Based Modelling(ABM) can efficiently predict collective behaviours of large as well as small crowds.
- Netlogo is recommended for developing prototype models with limited number of agents not more than 2000 agents.
- To model large scale simulation models with the range of hundreds of thousand agents FLAME platform is recommended.
- Crowd congestion in the *Sa'yee* ritual can be controlled better by defining strict rules for the allowed size of groups.

5.5 Future Work

For modelling the *Sa'yee* ritual we used the Agent Based Modelling (ABM) technique. This technique is a bottom up approach, in contrast with the top down approach of modelling the behaviour of the whole system through dynamic mathematical equations. ABM is a technique for the simulation of systems. In which the behaviour of a number of autonomous agents (in our case, pilgrims) acting simultaneously are specified. Despite the recognizable parallelism present in ABM systems, the traditional frameworks for ABM are still mainly based on highly serialised algorithms for manipulating mobile discrete agents, and fail to exploit the current high performance computational power available. NetLogo framework used in this thesis, for a single model run, used only one processor. In future to address this limitation of NetLogo framework we plan to use Flexible Large Scale Agent Modelling Environment (FLAME), that targets the high performance Graphic Processing Unit (GPU) architecture, and is called FLAME GPU. The FLAME GPU framework is designed with parallelism in mind. This design allows agent models to scale to massive sizes and hence ensures that simulations can run within reasonable time constraints. Implementing the *Sa'yee* model in FLAME GPU will allow us to carry out full-scale simulations. To optimize (further reduce the running time) the model, we will also look into other ways of using ABM to model and simulate the *Sa'yee* ritual, like modelling *Sa'yee* groups as one unit, etc.

It is impossible to build a general purpose model that will work for all the Hajj rituals. However, because of some similarities of the *Tawaf* and *Sa'yee* rituals (such as walking seven times either around *Kaabah* or between *Safa* and *Marwah*, etc), it may be possible to build a general purpose model for them. In future we will explore and research the designing and development of such a general purpose model that will work for both the *Sa'yee* and *Tawaf* rituals.

The proposed *Sa'yee* model in this thesis did not include the use of the entrance doors, shown in Figure 5.2, of the *Sa'yee* area. As part of the future work we would like to study the effects of the use of these entrance doors on the crowd behaviours and performance during the *Sa'yee* ritual.

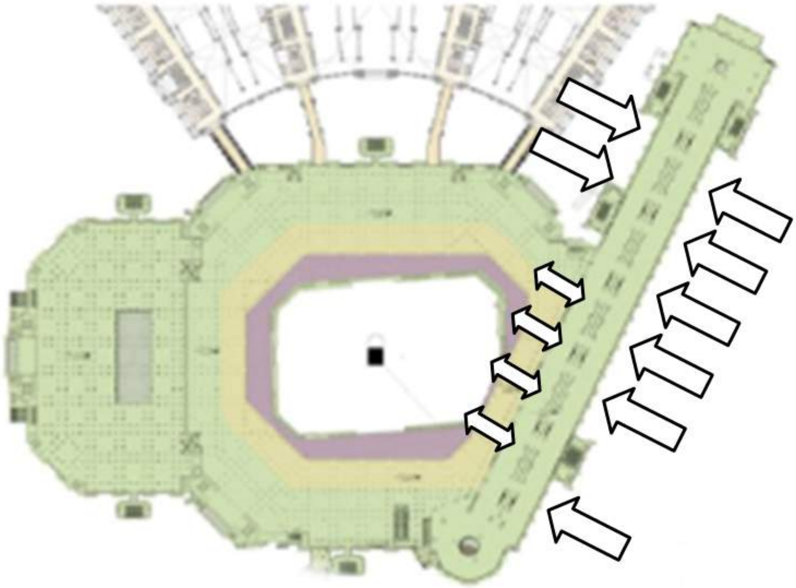


FIGURE 5.2: Depiction of the entrances and exits doors of the *Sa'yee* corridor from both sides.

We believe our work in this thesis provides a promising basis for future researchers interested in the area of modelling and simulation of the *Sa'yee* ritual to enhance the performance of the pilgrims.

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