HAJJ CROWD MANAGEMENT: Discovering Superior Performance with Agent-Based Modeling and Queueing Theory

by

Imran Khan

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Electrical & Computer Engineering
University of Manitoba
Winnipeg, Manitoba

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Abstract

The thesis investigates how Agent-Based Modeling and Simulation (ABMS) and Queueing Theory (QT) techniques help manage mass gathering (MG) crowds. The techniques are applied to Hajj MG, which is one of the most complex annual MG, with a focus on its challenging Tawaf ritual. The objective is to develop a Tawaf Decision Support System (DSS) to better understand Tawaf crowd dynamics and discover decisions that lead to superior performance. TawafSIM is an ABMS model in the DSS, which simulates macro-level Tawaf crowd dynamics through micro-level pilgrim modeling to explore the impact of crowd characteristics, facility layout, and management preferences on emergent crowd behaviours with respect to throughput, satisfaction, health, and safety. Whereas, TawafQT is a QT model in the DSS to explore the impact of pilgrim arrival rate and Tawaf throughput on expected arrival, departure, and waiting times along with average queue length in the Tawaf waiting area.

The thesis provides several contributions, including the following. First, it is the only Tawaf research to use a hybrid ABMS and QT approach. Second, TawafSIM is a comprehensive Tawaf simulator. It incorporates features for pilgrim characteristics, facility design, and management preferences. It calculates 8 metrics for Tawaf performance, which includes one for throughput, three for satisfaction, one for health, and three for safety. It is the only Tawaf simulator to estimate satisfaction and spread of infectious disease. It conducts 42 simulation experiments in 12 categories. It generates observations for emergent, tipping point, expected, and counter intuitive behaviours. It recommends a default scenario as the best decision along with a small subset of alternative scenarios, which provide above average Tawaf performance. It generates a Tawaf Crowd Management Guide to better understand Tawaf crowd dynamics and how to pursue above average Tawaf performance under different conditions. Third, TawafQT is the only study of the Tawaf waiting area. It uses an accurate queueing model with finite source, single service, and PH type distribution, which is not only applicable to the Tawaf and other Hajj related queueing systems but also to any queueing system, which has finite population and single service characteristics.

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CHAPTER 1

Introduction

The broad research topic of the thesis is managing crowds at mass gatherings (MGs) using Agent-Based Modeling and Simulation (ABMS) and Queueing Theory (QT) techniques. To understand how these techniques can better manage mass gathering crowds, the annual Hajj mass gathering is studied with an exclusive focus on modeling and simulating its most challenging Tawaf ritual. Before discussing the Hajj Crowd Management research, this chapter provides an introduction to MGs in general and annual Hajj MG in particular along with a synopsis of the remaining thesis.

1.1 Mass Gatherings

Mass Gatherings are diverse and common phenomena with inherent problems that need to be adequately researched and managed according to their level of complexity and potential of fatal outcomes. This subsection provides an introduction to MGs by providing its definition, showing its common occurrence, describing its inherent problems, proposing a scale to measure its magnitude, and discussing its importance in research and management.

1.1.1 Definition

There is no agreed upon definition for a mass gathering; however, most definitions share a common theme. "A mass gathering is 1000 or more people gathered in one place, usually with a common sense of purpose," as reported in [18]. While in [40] it is reported to be defined as "an organized event occurring within a defined space, which is attended by a large number of people" in [2], it is defined as "a large number of attendees at a specific event in a specified time." As such, taking the common themes in these representative definitions, this thesis broadly defines a MG as a large assembly of people at a specific place and time.

1.1.2 Common Phenomena

The above broad MG definition is appropriate since it accommodates the wide diversity of MGs. A description of several well-documented historical MGs is provided in [18] while a list of important MGs is found in [2], which includes the Olympics, Hajj, and World Youth Day. These examples show the wide diversity of MGs, which includes sports, entertainment, leisure, political, cultural, and religious events. Furthermore, MGs can occur at public locations for transportation, shopping, and education. The diversity of the MGs is also due to the different types of crowds that can form at MGs as reported in [40], which include: ambulatory, spectator, participatory, dense, and hostile. As such, it is important to recognize that MGs are not only those well-known planned complex events (e.g., Olympics) but also include the inherently common un-planned MGs that take place on a daily basis all over the world where there is a large assembly of people at a specific place and time (e.g., airport).

1.1.3 Inherent Problems

Due to the large assembly of people at a specific place and time, there are inherent problems linked with MGs. According to the historical review of MGs in [18], MGs increase the risk of injuries, deaths, medical emergencies, and illness primarily due to poor design of public buildings when a panic to exit the building often leads to people being crushed, which is sometimes due to a false fire alarm. Additionally, the literature review conducted in [38] for MG incidents from 1971 to 2011 identified the source of the MG problems to include: high crowd density, restricted access points, limited crowd control, and lack of sufficient on-site medical care and emergency response. Furthermore, it is suggested in [2] that increased travel to and from MGs is being linked to global outbreaks of infectious diseases. As such, MGs inherently have the potential for injuries, death, medical emergences, illness, and increasingly global outbreaks of infectious diseases due to high crowd density, restricted access points, limited crowd control, lack of sufficient on-site response, and increase of global travel to and from planned MGs.

1.1.4 Mass Gathering Magnitude Scale (MGM Scale)

Since MGs are common phenomena yet not all MGs are of the same magnitude, there is a need to have a scale to express the magnitude of the MG's potential fatal impact. As such, this subsection proposes a simple Mass Gathering Magnitude Scale (MGM Scale) to associate a number on a scale to the magnitude of a MG based on the MG's defining characteristics.

The proposed MGM Scale uses eight quantitative characteristics to define a MG. These characteristics can each take a MGM scale value of 1 to 10, which represent respectively the lowest and the highest expressions of the characteristics. The specific values of each of the characteristics that correspond to the 1 to 10 MGM scale is shown in Table 1, which have been chosen to accommodate the smallest and the largest values that are pragmatic for each MG characteristic. First, the *Total Number of Participants* is between 100 participants to 32 million participants. Second, the *Average Crowd Density* is between 1 to 10 participants per square meter. Third, the *Percent Maximum Flow Rate* is the average participant flow rate into the MG divided by the maximum participant flow rate possible into the MG. Fourth, the *Percent Maximum Time Participant in MG* is the average time participant is in the MG divided by the duration of the MG. Fifth, *Percent Time Participant Moving* is the average time a participant is moving while in the MG divided by the average time participant is in the MG. Sixth, *Percentage Non-Resident Participants* is the percent of participants who are non-residents at the MG. Seventh, *MG Duration* is from 1 hour to 512 hours (approximately 3 weeks). Finally, *Percent Cross Traffic* is the percent of participant movement in the MG where participants are not going in the same direction.

The average of these eight characteristic values for a specific MG provides the MGM scale value for the MG that is in the range 1 to 10, which respectively corresponds to minimal and extreme potential for fatal impact at the MG. As an example, the MGM scale values for Tawaf Hajj Ritual, Olympics Opening Ceremony, and Shopping Mall Boxing Day Sale are shown in Table 1. As such, the MGM scale provides a mechanism to quantitatively define and compare the potential fatal impact of diverse MGs so appropriate level of preparedness planning can take place by each of the MG organizers.

Table 1: Mass Gathering Magnitude Scale (MGM Scale) with examples

MGM CHARACTERISTICS	MGM SCALE 1	2	3	4	5	6	7	8	9	10
(1) Total Number of Participants[1]	100	1K	10K	100K	1M	2M	4M	8M	16M	32M
(2) Average Crowd Density[2]	1	2	3	4	5	6	7	8	9	10
(3) % Maximum Flow Rate	10	20	30	40	50	60	70	80	90	100
(4) % Maximum Time Participant in MG	10	20	30	40	50	60	70	80	90	100
(5) % Time Partici-pant Moving	10	20	30	40	50	60	70	80	90	100
(6) % Non-Resident Participants	10	20	30	40	50	60	70	80	90	100
(7) MG Duration[3]	1	2	4	8	16	32	64	128	256	512
(8) % Cross Traffic	10	20	30	40	50	60	70	80	90	100

Tawaf Hajj Ritual is 5.4 on MGM Scale using (7+7+1+1+10+6+6+5)/8.

Olympics Opening Ceremony is 3.5 on MGM Scale using (4+2+1+10+1+6+3+1)/8.

Shopping Mall Boxing Day Sale is 2.8 on MGM Scale using (2+1+1+2+8+1+4+3)/8.

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[1] K is thousands; M is millions.
[2] Participants per square meter.
[3] Hours.

1.1.5 Specialized Field of Research & Management

Since MGs have inherent problems with potential fatal consequences, MGs must be adequately studied and managed to prevent frequent fatal consequences. According to [18], historically, after repeated fatal catastrophes with MGs, the public outcry led to public safety legislation to carry out inspections of facilities before licenses were issued along with penalties for non-compliance, which were later broadened to include public health acts, which looked into construction and number of exits along with preparedness planning. It also states that public safety guides were developed to provide guidelines for safety. Furthermore, it states that MG organizers must secure the health and safety of those attending using event contingency planning and MG medical management specialities to provide among other things data analysis from past events and real-time crowd surveillance. This opinion is supported in [2] who also claim that MG Medicine needs to be a specialized, inter-professional branch of public health. As such, for the unplanned common MGs, it is pragmatic to provide public health and safety through legislation and guides, which outline legal requirements and best practices respectively. However, in general, planned complex MGs (e.g., Hajj) should go beyond existing legislation and guides to adequately research and manage the MG to provide adequate public health and safety.

1.2 Hajj Mass Gathering

The annual Hajj MG is one of the oldest, largest, and most complex MG. The subsequent subsections help to better understand the importance, rituals, and complexity of the annual Hajj MG, which makes the Hajj an example of a MG that requires specialized research and management to provide adequate public health and safety.

1.2.1 Hajj Importance

Islam is the second largest and the fastest growing religion in the world. Muslims (followers of Islam) believe there is only one God, Allah, who has created everything. In particular, humans have been created to worship and obey Allah as taught by the Prophets of Allah starting with Prophet Adam who was the first person on Earth and ending with Prophet Muhammad (peace be upon him) who is the last Prophet of Allah for all people to come until the end of time. In between Prophet Adam and Prophet Muhammad (peace be upon them), many Prophets came to guide a particular nation of their time to the same fundamental idea taught by all Prophets (i.e., believe, worship, and obey only one God), which includes the following well-known Prophets [14]: Idris (Enoch), Nuh (Noah), Hud, Salih, Ibrahim (Abraham), Ismail (Ishmael), Ishaq (Isaac), Yaqub (Jaqub), Lut (Lot), Shuayb, Yusuf (Joseph), Ayyub (Job), Yunus (Jonah), Musa (Moses), Harun (Aaron), Dawud (David), Sulayman (Solomon), Zakariyya (Zechariah), Yahya (John), and Isa (Jesus).

From among these Prophets, a few were given books of guidance by Allah, which include Prophets (peace be upon them): Ibrahim (Scrolls), Musa (Torrah), Dawud (Zabur or Psalms), Isa (Injil or Gospel), and Muhammad (Quran). All of these original divine books have either been lost or modified except for the Quran.

Islamic teachings convey that those people who believe, worship, and obey Allah as required by the most recent Prophet of their time will go to paradise for eternity while those people who do not believe, worship and obey Allah will go to hell for eternity. Thus, Muslims are required to follow the commands of Allah based on the Quran (original book in Arabic unchanged since revealed over 1430 years ago) and teachings of Prophet Muhammad (peace be upon him) as collected by early scholars of Islam. These two sources of guidance form the foundation of how Muslims must live their lives, which includes the five pillars of Islam each Muslim has to follow: (i) declare there is only one God and Prophet Muhammad (peace be upon him) is God's final messenger; (ii) pray five daily prayers; (iii) fast during the month of Ramadan; (iv) pay mandatory annual charity; and (v) perform Hajj pilgrimage.

1.2.2 Hajj Rituals

"Verily, the first House of worship appointed for mankind was that at Makkah, full of blessings, and a guidance for mankind and jinn. In it are manifest signs, for example, the station of Abraham; whosoever enters it, he attains security. And Hajj to the House (Kaaba) is a duty that mankind owes to Allah, those who can afford the expenses." [6]

As such, Hajj, which is a pillar of Islam, is an obligation on all Muslims who are financially capable of taking the pilgrimage to the Holy City of Makkah in Saudi Arabia to perform it correctly at least once in their lifetime. The annual Hajj occurs during the 8th to 13th days of Dhul-Hijjah of the Islamic Lunar Calendar. The key six steps of Hajj are discussed briefly, which are primarily based on [27].

1.2.2.1. Step 1: Prior to Hajj (Perform Visiting Tawaf & Saee)

Usually within two weeks before the first day of Hajj (i.e., 8th of Dhul-Hijjah), pilgrims arrive to Makkah (Figure 1) to make the visiting Tawaf and Saee at Al-Masjid Al-Haram (Figure 2, 3, 4, and 5). Tawaf involves circumambulation of the Kaaba counter-clockwise seven times, which can occur on ground, first, or roof floors. Each round begins and ends at the black stone line by touching or pointing to the black stone. It is recommended for men only to increase their speed in the first three rounds. After the seven rounds, it is followed optionally by praying behind the Abraham station if possible. Pilgrims then proceed to the Saee area to complete seven rounds between Safa and Marwah landmarks. The first round starts at Safa and ends at Marwah while the second round starts at Marwah and ends at Safa (each round is 0.5 km in distance). Only men should speed up the pace of walking between the two green marked posts between Safa and Marwah. After the Saee, men cut or shave their hair while women cut an inch off the bottom of their hair.

1.2.2.2. Step 2: Day 1 of Hajj (Stay in Mina)

On Day 1 of Hajj (i.e., 8th of Dhul-Hijjah), pilgrims move before noon prayer to Mina (Figure 6), which is an open desert area with permanent tents about 5 km east of Makkah, where they perform the 5 daily prayers and stay the night.

1.2.2.3. Step 3: Day 2 of Hajj (Attend Arafat & Muzdalifah)

On Day 2 of Hajj (i.e., 9th of Dhul-Hijjah), after morning prayers, pilgrims leave Mina for Arafat (Figure 7), which is an open desert area with non-permanent tents about 20 km southeast of Makkah. This is the most important ritual of Hajj in which pilgrims spend the whole day praising Allah and glorifying Him in order to seek forgiveness and guidance. After sunset, pilgrims leave Arafat for Muzdalifah (Figure 8), which is an open desert area about 9 km north of Arafat. Once in Muzdalifah, sunset and evening prayers are performed.

1.2.2.4. Step 4: Day 3 of Hajj (Day of Eid)

On the Day of Eid (i.e., Feast), which is Day 3 of Hajj (i.e., 10th of Dhul Hijjah), after the morning prayer, pilgrims leave Muzdalifah for Mina. When at Mina, pilgrims perform the stoning ritual at only the largest of the three pillars in the Jamarat area (Figure 9) to throw seven pebbles successively, which they gathered while at Muzdalifah. This is followed by three rituals usually in the following preferred order on Day 3 (alternatively they can also be performed on Day 4, 5, or 6): (i) making a sacrifice of a sheep, or 1/7 share of a cow or camel with other people, (ii) cutting or shaving the hair for men and trimming 1 inch of hair at the bottom for women, and (iii) making Tawaf and Saee in Makkah (referred to as Tawaf Ifadah). After finishing Tawaf Ifadah, pilgrims return to Mina to stay the night (note the minimum stay in Mina should exceed most of the night; otherwise, pilgrims are required to make a sacrifice).

1.2.2.5. Step 5: Days 4, 5, and 6 of Hajj (Rituals in Mina)

On each of days 4, 5, and 6 of Hajj (i.e., 11th, 12th, and 13th of Dhul-Hijjah), pilgrims go to the Jamarat area in Mina to throw seven pebbles at each of the three pillars starting with the smallest and finishing with the largest. Pilgrims should stay in Mina at least from midnight to morning prayer time. If pilgrims decide to stay only 2 days in Mina (i.e., Days 4 and 5 of Hajj), then they must leave Mina before sunset; otherwise, all pilgrims must leave Mina before sunset on Day 6.

1.2.2.6. Step 6: Perform Tawaf and Saee (Farewell Tawaf)

To complete the Hajj, before leaving Makkah, pilgrims must perform a final Tawaf and Saee (i.e., Farewell Tawaf).

1.2.3 Hajj Complexity

The Hajj is not only one of the oldest annual MG, compared to other MGs, the Hajj is much more complex. First, it involves a large number of pilgrims (approximately 4 million), which increases each year. Second, the Hajj involves performing rituals at four sites that are spread over a 20 km distance. Third, the four million plus pilgrims have to perform the same rituals within a predetermined time frame. For instance, all pilgrims move from Mina to Arafat between noon to sunset (maximum time), move from Arafat to Muzdalifah between sunset and dawn (maximum time), perform Tawaf Ifadah within 48 hours, and perform stoning at the Jamarat once each on three consecutive days. Fourth, multiple rituals take place over 5 to 6 day period. Fifth, the pilgrims come from all over the world speaking different languages with different customs. Sixth, although the transportation infrastructure has been greatly expanded in the last several decades, the increasing number of pilgrims creates gridlock in the transportation system between the Hajj sites. Finally, the Hajj involves significant physical hardships in performing the rituals in a primarily outdoor desert environment with limited modern amenities, especially for the old, young, and weak pilgrims.

1.2.4 Hajj Research & Management

Specialized Hajj research and management is a necessity due to the Hajj importance and complexity to provide a safe, healthy, and satisfying Hajj experience within the strict Hajj timeline. Over the past several decades, the number of pilgrims performing Hajj has increased significantly to the point were facilities and policies at times become inadequate to handle the large movement of people between Hajj related sites and at the individual Hajj sites. There are many Hajj aspects that have been studied: (i) the arrival of pilgrims into Saudi Arabia at airports and roads, (ii) Tawaf and Saee ritual in Makkah, (iii) stoning at Jamarat, (iv) movement of people between Arafat, Muzdalifah, and Mina, (v) movement of pilgrims between Makkah and Medina, (vi) accommodation arrangements at Makkah, Medina, Mina, Arafat, and Muzdalifah, (vii) medical facilities, and (viii) security arrangements. These studies have resulted in many sophisticated and expensive Hajj expansion projects costing billions of dollars, which were developed by the Kingdom of Saudi Arabia.

All of these studies (both past and future) are important. First there have been many casualties over the years, caused by trampling to death of hundreds of people at the Jamarat area and broken bones due to uncontrolled crowd movement during Tawaf Ifadah. Second, due to the large number of pilgrims coming from all over the world, there have been diseases spread during Hajj and also diseases spread back to home countries. Third and most important, if the Hajj is done accurately with pure intention and accepted by Allah, than it will remove all the past sins that a person has committed. Fourth, as the number of pilgrims performing Hajj increases each year, the current facilities become more congested, and for some Hajj sites, the over crowdedness becomes a safety and health concern. As such, it is essential not only to keep expanding the Hajj sites, it is equally important to better manage the current Hajj sites to accommodate the large number of pilgrims. Thus, it is very important to research the Hajj process continually to improve the Hajj management process to accommodate the steadily increasing number of annual pilgrims in order to give the pilgrims a better chance to have an accepted Hajj.

1.3 Thesis Synopsis

In chapter 2, the Hajj crowd management research topic is presented, which begins with the identification of the research problem and objective. It then provides a sample literature review on Hajj research studies and comprehensive literature review on Tawaf crowd models along with insights learned for future Hajj crowd management research. Chapter 3 provides an overview to DSS, ABMS, QT, difference between ABMS and QT, and TawafDSS, the Tawaf crowd management decision support system developed in the thesis to address the research problem and objective. Chapter 4 discusses the details of the Tawaf ABMS simulator, TawafSIM, which includes: objective, implementation, simulation observations, validation, and results. While chapter 5 discusses the details of the Tawaf waiting area QT model, TawafQT, which includes: objective, implementation, validation, numerical examples, and results. Finally, chapter 6 provides concluding remarks on recommendations, limitations, contributions, and future work.

Figure 1: Hajj ritual site locations

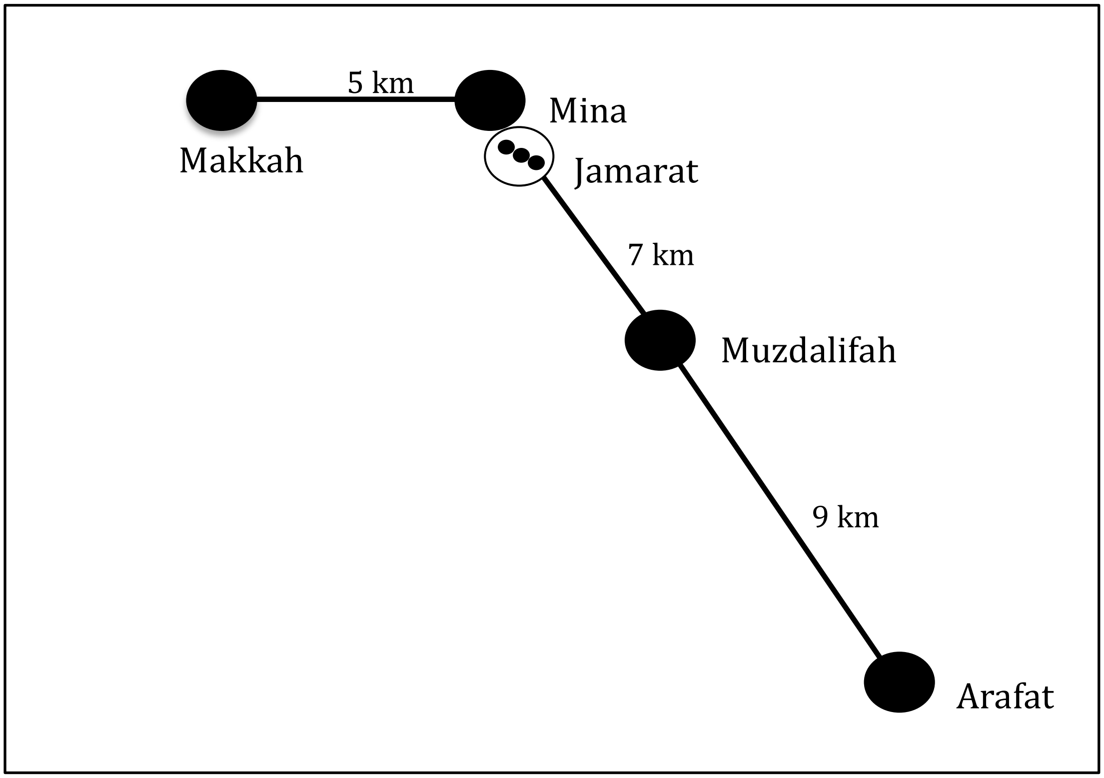


Figure 2: Al-Masjid Al-Haram layout

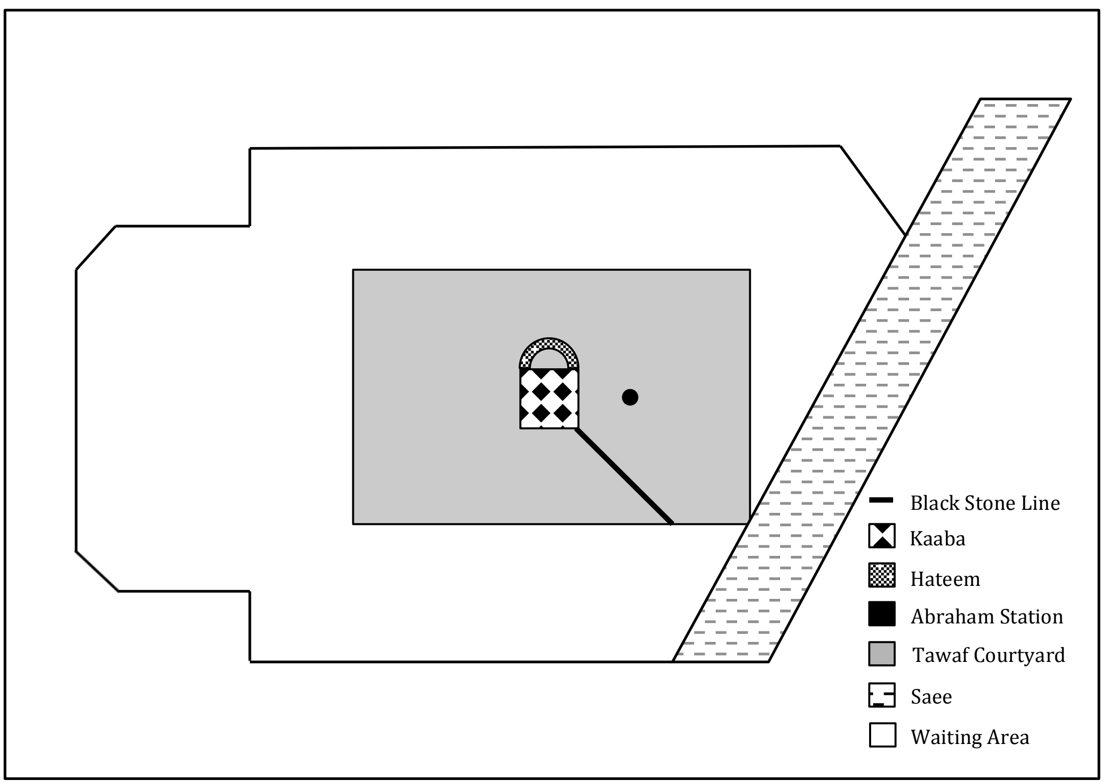


Figure 3: Tawaf courtyard in Al-Masjid Al-Haram

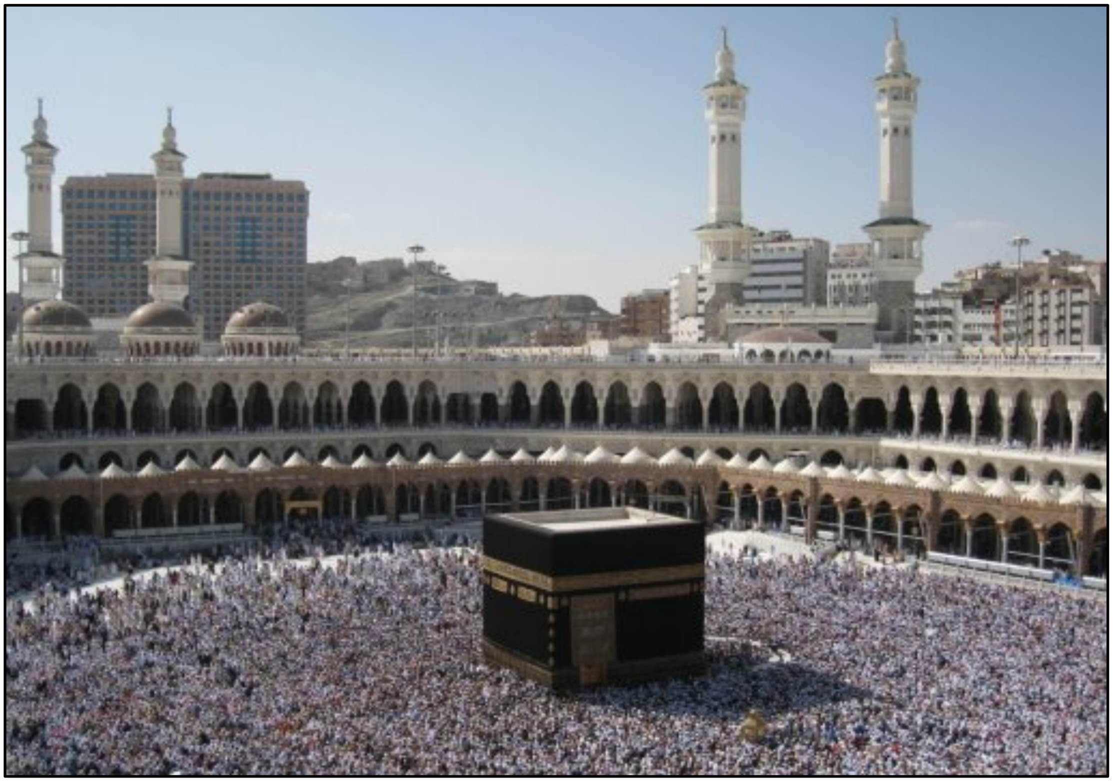


Figure 4: Tawaf crowd around Black Stone of Kaaba in Al-Masjid Al-Haram

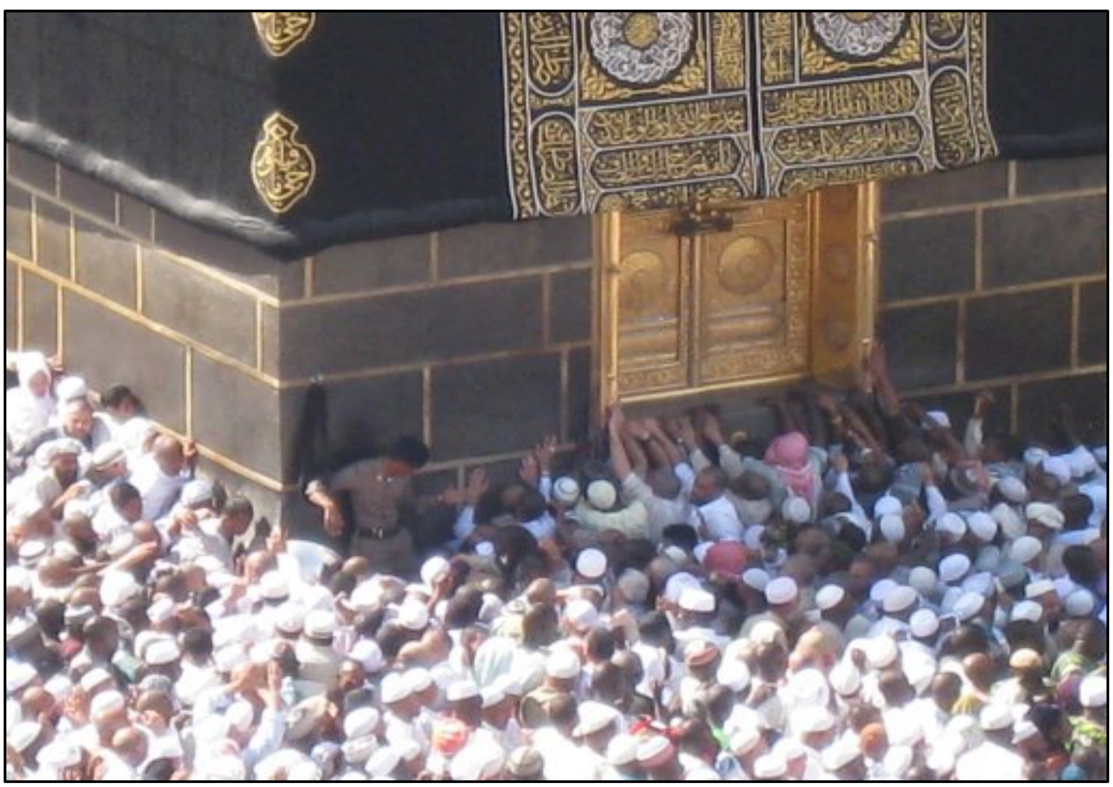


Figure 5: Tawaf crowd at Abraham Station in Al-Masjid Al-Haram

Figure 6: Mina tent city

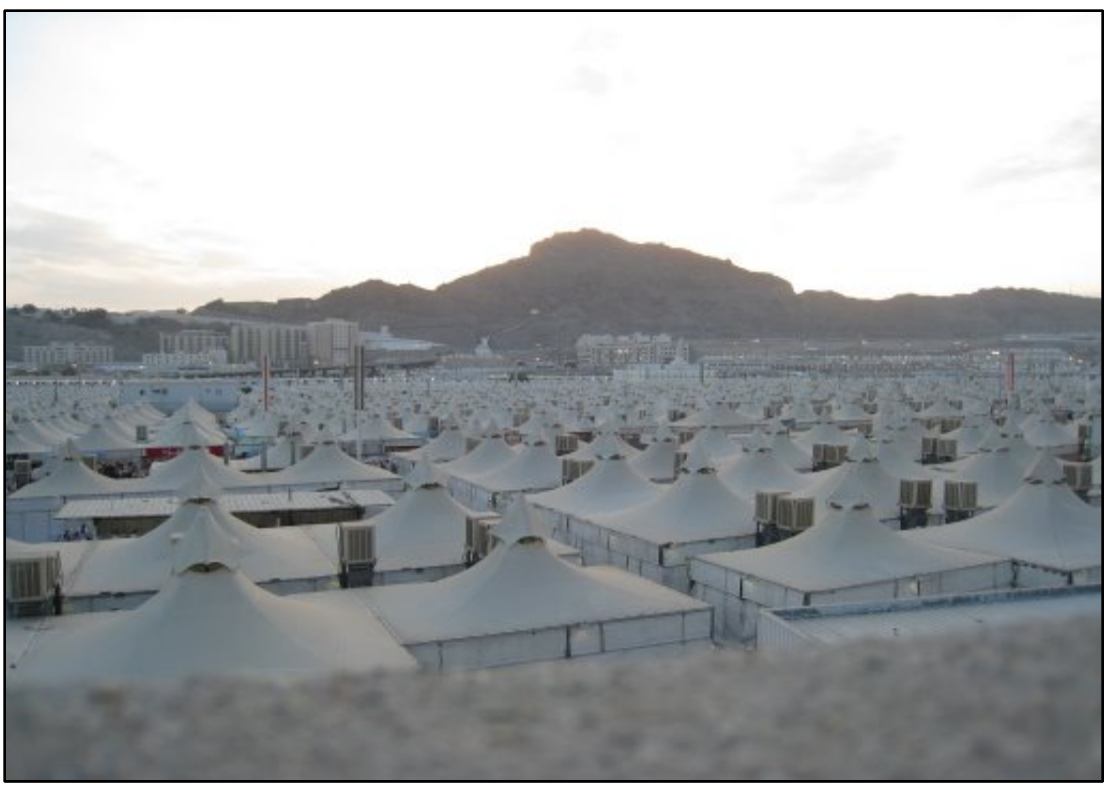


Figure 7: Arafat at sunset

Figure 8: Muzdalifah at night

Figure 9: Jamarat wall

CHAPTER 2

Hajj Crowd Management Research

Hajj Management is defined as the set of management decisions to plan, organize, lead, and control every activity associated with the annual Hajj mass gathering whereas Hajj Crowd Management is defined as the set of management decisions associated with Hajj rituals in Saudi Arabia, which lead to superior crowd performance, with respect to throughput, safety, satisfaction, and health conditions.

This chapter begins with a description of the research problem and objective. It then provides a sample literature review on Hajj research studies and a comprehensive literature review on Tawaf crowd models along with insights for future Hajj crowd management research.

2.1 Research Problem & Objective

Hajj crowd management is a complex problem. It meets the four common characteristics of complex problems as defined by Michalewics et al. [25]: (i) complex constraints, (ii) time-changing environment, (iii) several conflicting objectives, and (iv) large number of possible solutions. As such, it is difficult to determine which Hajj crowd management decisions lead to superior crowd performance.

Modelling complex problems and systems with ABMS and QT techniques have been shown to help better understand and solve problems. ABMS has been used in a diverse range of management problems, including supply chain management, energy distribution, and crowd management. Similarly, QT has been extensively used in traffic flow, scheduling, and facility design management decision-making problems. As such, ABMS and QT can provide insight into management decision-making.

To understand how ABMS and QT techniques can help better manage Hajj crowds, the research focuses on modeling and simulating the Hajj's most challenging Tawaf ritual. As such, the specific research problem addressed in the thesis is which set of Tawaf crowd management decisions can lead to a superior crowd performance, with respect to throughput, satisfaction, health, and safety conditions?

This research problem is extremely important. First, Tawaf throughput is challenging since all pilgrims must perform it in the fixed 48-hour timeframe. Second, satisfaction (i.e., peace-of-mind) is an issue since the Tawaf is an act of worship that must be done properly with full devotion. Third, health concerns are an issue for the pilgrims and also globally, considering the potential global outbreak of infectious diseases. Fourth, safety is an issue given the large number of pilgrims with high crowd density over a short timeframe. Finally, Tawaf is part of Hajj, which is a pillar of Islam that all financially capable adult Muslims must fulfill correctly at least once in their life to have all their past sins forgiven.

As such, the objective of the thesis is to better understand which management decisions lead to superior Tawaf crowd performance by developing a Tawaf Decision Support System (i.e., TawafDSS) to model the micro-level behaviour of Hajj pilgrims performing the Tawaf ritual in order to explore the impact of crowd characteristics (e.g., gender, manners, speed, strength, desires, and health), facility layout (e.g., number of entry points), and management policies (e.g., rate of entry and maximum people) on emergent crowd behaviour (i.e., throughput, satisfaction, health, and safety conditions) during the complex crowd movements.

2.2 Hajj Research Literature Review

This section provides a sample literature review of Hajj ritual related research studies published in English, which provide insight into Hajj simulation models. In particular, one paper on pilgrim shuttle bus transportation system and two papers on the Jamarat are highlighted, which provide good general insight for developing Hajj related simulations.

2.2.1 Al-Sabban & Ramadan: Shuttle Bus Simulation

Al-Sabban and Ramadan [7] state that the transportation of pilgrims between Mina, Arafat, and Muzdalifah was studied as early as 1990 because the 10-minute normal travel time between Muzdalifah and Arafat (a 5 km 9-lane segment) would take 3 hours during Hajj. As a result of the large waiting time and increasing number of pilgrims each year, the Ministry of Hajj created an experimental project in 1996 using a pilgrim shuttle bus transportation system. Almost a decade after the launch of the shuttle bus, Al- Sabban and Ramadan evaluate the constraints and shortcoming before further expanding the shuttle bus system.

The approach used in this study is as follows: identify controlled variables, identify output variables, measure real time traffic for variables, model system using mean measured attributes with distribution of random variable, run system with distribution, and measure output variables for different scenarios after model is validated for known scenario. After calibration, the model is run for new future scenarios to determine how many buses and drivers would be needed to transport the pilgrims from Mina, Arafat, and Muzdalifah. In particular, the research shows that more than 542 or less than 466 buses does not decrease the transportation time. Although this simulation is quite simple, it shows that the Ministry of Hajj is interested in simulations to learn how to improve efficiency within the given constraints.

2.2.2 Al-Haboubi: Jamarat Redesign Simulation

In [4], Al-Haboubi provides a new layout design for the Jamarat area to solve its severe congestion problem. He states that the problem is the crowd density increases as pilgrims approach the stoning pillar target and, more importantly, the cross traffic created by pilgrims finishing the ritual creates unprecedented conflicting large-scale movement. Furthermore, he states the large crowd not only creates a safety issue but also Islamic and ethical issues as the bodies of opposite genders should not come in contact.

Al-Haboubi proposes several solutions: (i) multi-level bridge, (ii) scheduling (which he claims is difficult to enforce), (iii) encourage uniform density flow (which he claims is difficult to control due to multiple pilgrim languages), and (iv) new layout.

Al-Haboubi recommends a new layout, which he simulates for two age groups, three walking times, and six different numbers of total pilgrims. The new layout involves controlling the unidirectional flow of movement using parallel lanes, which increase in elevation on either side from the center lane using barriers that start before the first Jamarat and finish after the third Jamarat.

Although it is possible to control the cross traffic issue in the Jamarat area by expanding capacity using the multi-level bridge, Al-Haboubi chose to recommend a solution with an extreme modification to the existing stoning rituals (i.e., raised parallel lanes), which is probably why it was not considered a feasible new layout.

2.2.3 Klupfel: Jamarat Crowd Simulation

A second Jamarat study is conducted by Klupfel [20] who conducts a simulation of crowd dynamics at three large events: Jamarat, World Youth Day 2005, and a football stadium. His Jamarat simulation is for 100,000 people uniformly distributed on the bridge. The simulation shows how the crowd disperses when the route choice for the simulation is based on static field concepts (also known as potential or distance metric).

Although Klupfel's simulation is simple, he provides some interesting insights. He states simulation results are strongly determined by choice of parameters, especially route choice strategies. He further states that since route-choice is normally not a result of the simulation but is a defined simulation parameter, an artificial intelligence approach is necessary for route choice, which requires a mental representation of the geometry every agent can access.

2.3 Tawaf Research Literature Review

This section begins with a brief overview of the different approaches for crowd simulation. It then describes five important Tawaf crowd research studies, which may provide insight for developing Tawaf crowd simulations. The first paper suggests a redesign to the Tawaf process to enhance performance. The second study analyzes the Tawaf movement using GPS. The next two papers simulate the Tawaf crowd using the Cellular Automata approach, while the last paper uses the agent-based approach.

2.3.1 Crowd Modelling Approaches

There are four general approaches to crowd modeling. The first approach to crowd modeling assumes pedestrians are like particles that are subjected to forces, which are governed by fixed equations. In [17], the fluid dynamic analogy and equations used to represent aggregate pedestrian behaviour in the past is replaced with the social forces analogy and equations, which the authors claim is able to model individual pedestrians at small pedestrian densities. In [30], individual pedestrian movement is modeled using equations for the motion of a magnetized object in a magnetic field, where pedestrians are positive poles and pedestrian goals are negative poles.

The second approach to crowd modeling is based on the cellular automata concept [31] where cells in a 2-dimensional grid can take on a discrete number of values that are updated in discrete time steps according to a set of rules, which depend on the values of cells in a neighbourhood around it. In [11] the cellular automata concept is used to model bi-directional pedestrian walkways, where they claim a small rule set captures the micro-level behaviours of pedestrians to simulate macro-level behaviour.

The third approach to crowd modeling is based on the agent-based concept. In [9], a Situated Cellular Agent approach is used to model pedestrians as a set of agents that are situated in a set of cells and act autonomously through the propagation of a set of fields. This specific agent-based approach seems to be influenced by both cellular automata and agent based concepts.

The shortcoming for all the above crowd modeling approaches is that these models do not have a simple and natural pedestrian model for attributes, behaviours, perception, and adaptation rules.

2.3.2 Al-Haboubi & Selim: Tawaf Redesign Solution

In [5] Al-Haboubi and Selim present a design to minimize congestion around the Kaaba by eliminating cross traffic. They state those who have completed Tawaf and those who have just arrived or are at the early stage of the ritual cause cross traffic. In particular, those who have completed Tawaf find themselves close to the Kaaba and need to walk outward while those performing Tawaf make inward movements as pilgrims move to replace the area occupied by those who have completed Tawaf. They further claim the cross traffic phenomena creates three problems: (i) safety (e.g., breathing problems), (ii) distraction from spiritual submission (i.e., too crowded with contact between opposite genders), and (iii) long time delays (2 to 3 times longer). Al-Haboubi and Selim propose potential solutions: (i) schedule admittance (but claim it is difficult to schedule and control a large crowd), (ii) construct second floor around Kaaba in courtyard (but claim it would obstruct view of Kaaba), (iii) control inflow to Kaaba courtyard under a maximum capacity, and (iv) build spiral path around Kaaba which encircles it seven times then at the Kaaba there is a ramp leading to underground dispersion area (but claim pilgrims would have to be brought back for Saee ritual).

Al-Haboubi and Selim recommend the spiral path approach and present an optimal width of the spiral for different population sizes, which minimizes total waiting time in the system as a function of spiral path width and level of service (i.e., flow rate, speed, space/person). Although they resolve the cross traffic problem, the design is too artificial, which makes the Tawaf like an amusement ride, which is probably why it has not been adopted.

2.3.3 Koshak & Fouda: Tawaf GPS Crowd Analysis

Koshak and Fouda [21] analyze the pedestrian movement in Tawaf areas using GPS and GIS (i.e., Geographic Information System) to support space redesign. They claim the research is important because much of the previous Tawaf crowd analysis was based on human visual observation using video recordings.

Koshak and Fouda use GPS devices to collect spatial-temporal data by four trained students at different times and then use GIS to analyze the spatial-temporal data. Specifically, students simulate a person performing Tawaf to collect data on position, date, and time every 15 seconds from the courtyard and roof during the 10^{th}, 11^{th}, and 12^{th} of Dhul-Hijjah when the crowds are the largest. During these three days, each student goes around the Kaaba once every hour between 10 am to 9 pm. The data is then converted into a temporal geo-database to represent Tawaf tracks.

Koshak and Fouda found that a person performing Tawaf on the roof completed one round before a person performing Tawaf in the courtyard, even though the distance around the roof is larger because the courtyard is so crowded. As well, the research identified seven zones in the Tawaf area with different velocities.

Although the analysis of the Tawaf is slightly out-dated (the courtyard used to have a painted start line on the floor, which caused significant delay at the start line) and the seven velocity zones were identified with only four GPS units during half of the 48-hour Tawaf Ifadah period, Koshak and Fouda provide measured Tawaf crowd data that may be used to validate Tawaf simulation models.

2.3.4 Abdelghany et al.: Cellular Automata Based Tawaf Simulation

Abdelghany et al. [1] simulate the Tawaf area using a micro simulation assignment model and claim dynamic micro level simulation has gained acceptance as a modeling approach to study pedestrian dynamics in crowds. The novel contributions of the model are: (i) dynamic adjustment of destination and movement direction as conditions change in the system and (ii) concept of a congestion aversion factor.

Abdelghany et al. state existing pedestrian microscopic simulation models share several limitations with respect to the underlying pedestrian behaviour rules. First, most models assume each pedestrian has only one destination in the area. Second, most models assume the pedestrian destination is fixed and does not change with the system's dynamics. Third, most models consider limited locations toward which a pedestrian can switch movement direction. Fourth, most models incorporate a small number of pedestrian characteristics (e.g., speed and congestion aversion) but ignore other factors (e.g., age, gender). Finally, most models consider a limited number of adjacent cells, which a pedestrian can move to at any time.

In comparison, given a layout of a pedestrian facility and pedestrian demand, the Abdelghany et al. model assigns each pedestrian a value to represent maximum free-flow speed and a parameter value for congestion tolerance, which produces pedestrian trajectories that determine the aggregate temporal and spatial traffic distributions. Furthermore, their model has four components in their pedestrian micro simulation assignment model. First, the area configuration component defines the pedestrian facility using a CA, where one cell can accommodate one pedestrian. Second, the demand-loading component manages the entry of the pedestrians into the pedestrian facility via entry cells that are adjacent to entrances. As such, on arrival, a pedestrian either enters the entry cell if it is empty or waits in its queue. Third, the user behaviour and assignment component models user decisions by choosing destination, movement direction (using straight line sight scan), congestion perception, and congestion aversion attitude levels. Finally, the simulation component captures the collective effects from all the individual pedestrian decisions.

Abdelghany et al. conduct five experiments to illustrate the capability of simulating pilgrim movement in which time-dependent system throughput as a percentage of the total loaded demand is recorded along with the average speed of pilgrims. The experiments model 50 m radius around the Kaaba, and each experiment has the following common parameters: demand level of 6,700 pilgrims over 2-hour period, exit in direction of flow, free-flow speed of 0.5 m/s, and congestion aversion of 0.5 (i.e. maximum congestion level in target cell at or below which a pedestrian would accept moving into the cell; thus if the target cell is empty and the target congestion level is below the congestion aversion level, the pedestrian moves into the target cell). The first experiment studies the system under different congestion levels (i.e., 5,200, 6,700, and 10,050) over a 2-hour period.

The second experiment studies the impact of spatial demand loading pattern on system performance under three scenarios: demand loaded uniformly along the perimeter of the outer ring, demand loaded through four equally spaced gates along the outer perimeter, and demand loaded through two gates at opposite sides of the outer ring. The third experiment studies the effect of conflicting traffic, with three percentages of pilgrims exiting in clockwise direction: 0%, 50%, and 100%. The fourth experiment studies the impact of two free-flow speeds (i.e., 0.5 m/s and 1.0 m/s) on system performance for three scenarios: 100% pilgrims at 0.5 m/s, 75% pilgrims at 0.5 m/s, 25% pilgrims at 0.5 m/s. The final experiment studies the impact of the degree of congestion aversion (i.e., 0.75 congestion aversion is set for a congestion seeker and 0.5 is set for a congestion-averse individual) on the system throughput for three scenarios (i.e., ratio of congestion-averse to congestion seeker): 40:60, 50:50, and 60:40.

Abdelghany et al. state the experiment results suggest several observations. First, as more pilgrims increase in the courtyard, the congestion level, the average travel speed, and overall system throughput decrease. Second, they suggest using large number of entrances reduces the number of high-density locations, which increases average pilgrim speed and system throughput. Third, as the percentage of pilgrims flow in opposite directions, the system throughput decreases. Fourth, as the percentage of pilgrims with high-speed increases, the throughput increases. Fifth, as the number of congestion-aversion pilgrims increase, the pilgrims tend to disperse themselves, which increases average travel speed and system throughput.

Although the Abdelghany et al. model does not model maximum crowd capacity, praying behind Abraham station, mini-crowd around black stone, different congestion zones, pushing forces, and no advanced features (i.e., adaptability, perception model, and internal model), this is the most beneficial model with its five experiments, which illustrates the capability of the simulator with insightful observations. The model, however, has some limitations: only models pilgrim speed and congestion tolerance; uses the CA rather than the more natural ABMS approach; calculates only throughput and average speed; and has a limited number of experiments. Finally, it is noteworthy that Abdelghany et al. provide a disclaimer that the actual use of their model to support crowd management decisions requires careful adaptation and calibration to the system, supported by observation and measurement.

2.3.5 Sarmady et al.: Cellular Automata Based Tawaf Simulation

In [33, 35, 37], Sarmady et al. simulate the Tawaf crowd using a multi-layer model for human actions and movements. First, the Multiagent Behaviour Simulation (MABS) unit builds the crowd using demographic data, which builds autonomous agents from a template. Second, the Micro-macro Crowd Simulation (MiCS) unit provides microscopic agent movement using cellular automata model and macroscopic movement using static path tables between possible destinations. The steps in their algorithm are: (i) read geometry data, (ii) receive actions from MABS unit, (iii) select path to achieve action for macroscopic movement, (iv) simulate microscopic agent movement using CA in MiCS, and (v) record results.

The model assumes there are a limited number of logical and suitable paths in static path tables between every source and destination, in which better routes have lower cost; thus, pedestrians choose one of these routes based on their own knowledge, MABS, or randomly. With respect to the Tawaf movement, pedestrians try to maintain circular movements about the Kaaba. Furthermore, the characteristics of individual agents are represented using: age, orientation/way finding capability, gender, health, energy, fatigue, desired speed, and stress.

Sarmady et al. claim when the simulation is run with random initial pedestrian position with a delay at the Tawaf start line, the preliminary results are comparable to Tawaf video footage. Although the model captures some attributes of pilgrim movement, it makes many assumptions to simplify the model: route selection based on static path tables, same speed for all pilgrims, and leaving out key Tawaf dynamic behaviour (e.g., crowd around black stone and Abraham station, cross traffic, and pushing). As well, it is missing advanced behaviour features (i.e., perception model, internal model, and adapt decision rules). Thus, it is interesting that the model with many oversimplifications and missing advanced features still produces simulation results comparable to Tawaf video footage. Finally, the biggest area for improvement in their work is the addition of a comprehensive set of experiments illustrating the capability of the simulator.

2.3.6 Curtis et al.: Agent Based Tawaf Simulation

Curtis et al. [12] model the Tawaf movement using an agent-based model, which combines finite state machine (e.g., states for: circle, circle done, touch Kaaba, pause, and exit) to specify pilgrim behaviour at each time step along with a geometric collision-avoidance algorithm for interaction with its neighbours. They state the Tawaf crowd is challenging to simulate because the crowd moves with multiple purposes (i.e., enter, exit, circle, or pause), has up to eight pilgrims per square meter with varying velocities, and complex motion flows (e.g., pause, touch Kaaba, circle Kaaba, move orthogonally, inwards, outwards to the circular flow). They model age and gender by varying speed along with other parameters, which control how the agents pursue their goals. The simulation measures crowd density and velocity along with time to complete Tawaf and throughput of the system. Although they compare their results with the limited Tawaf crowd GPS data in [21], they state an accurate Tawaf crowd simulator remains an open problem. The simulator is used to explore the impact of heterogeneous population (i.e., gender and age) on the throughput of the Tawaf. In particular, it claims a 100% young male crowd versus a 100% old female crowd would have a throughput of 58,600 and 52,700 respectively. Finally, the biggest area for improvement in their work is the addition of a comprehensive set of experiments illustrating the capability of the simulator.

2.4 Literature Review Insights

There are many insights learned from the previous two literature reviews on Hajj research and Tawaf crowd research, which can be useful for future Hajj crowd management research initiatives.

First, the Ministry of Hajj is interested to use simulations to improve the efficiency of current processes before further expansion plans. Second, cross traffic crowd movement creates issues for safety, distraction between genders, and delays. Third, solutions to reduce cross traffic include: facility expansion, pilgrim scheduling, pilgrim capacity, and facility layout redesign. Fourth, solutions with extreme modifications to Hajj rituals are not adopted. Fifth, pilgrim route selection in simulations should be dynamically chosen based on incremental simulation results and not determined simulation parameters.

Sixth, up-to-date Tawaf crowd analysis using GPS and other techniques are important for validating simulations. Seventh, models with significant simplifications (e.g., less than full courtyard modeling, praying behind Abraham station, mini-crowd around Black Stone, pushing forces, and group movement) seem to produce well-known visual Tawaf crowd patterns. Eighth, it is challenging to model the Tawaf crowd because pilgrims have complex movement behaviours. Ninth, simulations should measure at least Tawaf performance for crowd density, Tawaf time, and throughput. Tenth, simulation experiments for impact on Tawaf performance should be conducted for: maximum pilgrims, number of entrances, pilgrim speed, pilgrim congestion aversion, and cross traffic level. Finally, several essential Tawaf crowd features should be modeled: dynamic adjustment of destination and movement direction; pilgrim congestion aversion, comprehensive pilgrim characteristics; large number of adjacent cells for pilgrims to move to; and pilgrim movement based on pilgrim characteristics and local conditions.

CHAPTER 3

TawafDSS: Tawaf Crowd Management DSS

This subsection begins with a brief introduction to the Decision Support Systems (DSS) concept, which can help make better management decisions. Next, Agent Based Modelling and Simulation (ABMS) and Queueing Theory (QT) modeling techniques used in the thesis to implement the DSS are described. Finally, TawafDSS, the Tawaf crowd management DSS developed in the thesis is introduced.

3.1 DSS Overview

According to [23], the value of an activity can significantly increase by improving its decision-making process, especially for unstructured decisions where there is no well-understood or agreed-on procedure for making them. Furthermore, a DSS provides analytical models and tools to better understand the problems and discover solutions associated with the activity. Although there are many modelling techniques available to develop a DSS, since the focus of the thesis is on modelling micro- and macro-level crowd dynamics behaviour, Agent-Based Modeling and Simulation (ABMS) and Queueing Theory

(QT) approaches are good modelling techniques. As such, the following subsections provide an overview of ABMS and QT approaches respectively.

3.2 ABMS Overview

North and Macal [29] argue modeling and simulation are useful in decision-making. First, it is difficult to understand how all the various parts of the system interact to create emergent behaviour. Second, it is difficult to imagine all the possibilities that the system can exhibit. Third, it is difficult to foresee the full effects of events with limited mental models. Fourth, it is difficult to imagine novel events outside of limited mental models. Fifth, it allows managers to experiment to gain insight into key variables and their causes and effects. Finally, it allows managers to make predictions of the future.

Agent Based Modeling and Simulation (ABMS) is a technique to model micro-level behaviour of individual system components to simulate macro-level emergent outcomes. During the ABMS process, a large number of combinations (i.e., configurations) for management choices and environmental factors are considered, which leads to the identification of poor and superior choices. This subsection provides an overview of ABMS concepts primarily based on North and Macal.

According to North and Macal, an agent can be defined as a decision-making entity in a complex adaptive system with a set of attributes and behavioural characteristics. The attributes define what the agent is, such as, agent objective while agent behaviour defines what the agent does, which includes (i) decision rules to select actions, (ii) adaptive capability to learn from experiences, (iii) perception capability to sense its surroundings, and (iv) internal model to project possible consequences of decisions. In particular, the agent behaviour materializes through five steps: (i) evaluate current state, (ii) determine what to do, (iii) execute the action chosen, (iv) evaluate results of the action, and (v) adjust rules based on results. This behaviour can be developed with simple behaviour rules implemented with if-then statements, complex behaviour rules implemented with nested if-then statements, or sophisticated behaviour modeled with advance techniques, such as, statistical methods (e.g., multinomial logit), artificial intelligence methods (e.g., artificial neural networks), and optimization methods (e.g., genetic algorithms).

According to North and Macal, the ABMS approach is useful when: (i) the problem has a natural representation as consisting of interacting agents, (ii) there are decisions and behaviours that can be defined discretely, (iii) it is important that agents adapt and change their behaviour, (iv) it is important that agents learn and engage in dynamic strategic behaviour, (v) it is important that agents have dynamic relationships with other agents, and agent relationships form and dissolve, (vi) it is important that agents form organizations, and adaptation and learning are important at the organization level, (vii) it is important that agents have a spatial component to their behaviours and interactions, (viii) the past may be a poor predictor of the future, (ix) scaling up is important, and scaling up consists of adding more agents and agent interactions, and (x) process structural change needs to be a result of the model, rather than an input to the model.

3.3 QT Overview

In a queueing system, customers arrive for service, wait for service if it is not available, and leave the system after being served. Queueing theory provides mathematical models to predict the waiting behaviour of systems when the demand for a service is greater than the service available. Applications of queueing theory have been applied to a broad range of management decision-making problems, which include traffic flow, scheduling, and facility design. Although real problems cannot match mathematical models, complex computational analysis, approximate solutions, and sensitivity analysis are providing practical value. As such, queueing theory helps answer questions such as: how long must a customer wait in line before getting served? how many people will form in the line?

According to Gross et al. [16] queueing processes can be described by six characteristics. First, the arrival pattern of customers, which is described with random variables, specifies: the probability distribution of the customer interarrival times, single or batch arrival, state-dependent arrival (i.e., reaction of impatient customers upon entering the system, such as, balking, reneging, jockeying), and stationary or nonstationary arrival pattern with respect to time. Second, the service pattern, which is also described with random variables, specifies: probability distribution for customer service times, single or batch service, state-dependent service (i.e., speed of server as function of queue length), and stationary or nonstationary service pattern with respect to time. Third, the queue discipline specifies how customers are selected for service, such as: first-in-first-out, last-in-first-out, random order, round robin, or priority based. Fourth, the system capacity specifies the size of the waiting queue (i.e., finite or infinite). Fifth, the number of service channels specifies the number of parallel service stations. Finally, the stages of service specify whether there are single- or multi-stages of service.

Furthermore, according to Bhat [10] the most common application of queueing theory is to study the behavioural problems of queueing systems, which help understand how the system behaves under various conditions. Mathematical models for the probability relationships among various elements of the process are used in the analysis. The major characteristics of interest are: number of customers in the system (i.e., queue length), amount of time a new arrival waits for service to begin (i.e., waiting time), and length of time server is continuously busy (busy period). The queue length and waiting time are stochastic processes while the busy period is a random variable. The distribution characteristics of these items are determined in the queueing analysis to understand the system behaviour. As well, since time is a factor, distinction is made between transient and steady state behaviour.

In order to solve these mathematical queueing models, the traditional method depends on inverting generating functions and/or Laplace transforms to derive usable results. The more sophisticated matrix-analytic method [3, 28] extends and modifies the transform method to multivariables and uses an algorithmic solution.

3.4 ABMS versus QT

To simulate, or not to simulate, that is the question when deciding whether to use the ABMS approach or the QT approach to model a system. The answer depends on several factors associated with the characteristics of the system being modeled. For many systems, both approaches can be used as in [22], however, the following general guidelines may identify one approach more suitable than the other.

First, if the emergent system outcome is influenced by the individual agent behaviour, then the ABMS may be a better choice despite its generally greater complexity in programming the model; otherwise, QT is generally less complex to develop and may provide a comparable analysis. Second, if the arrival and service distributions are not available for an existing system or cannot be accurately approximated, then QT may not be a good choice; instead, ABMS could be developed since it does not rely on the distributions. Third, if the underlying behaviour of the system leading to emergent outcomes cannot be defined accurately, then QT may be a better choice since the ABMS relies on micro-level agent behaviour. Finally, if an existing system will be used in a new scenario without any prior knowledge of how the system will respond, then the ABMS approach may be more suitable than the QT approach.

3.5 TawafDSS Overview

TawafDSS is the Tawaf crowd management DSS developed during this research to help better understand Tawaf crowd management decisions by exploring the impact of crowd characteristics, facility layout, and management policies on superior Tawaf crowd throughput, safety, satisfaction and health conditions. Although Chapters 4 and 5 describe in detail the TawafDSS components, this subsection describes which specific Tawaf related activities to model along with which modeling and simulation technique is most appropriate for each activity.

Potential changes to Tawaf crowd management decisions with respect to shaping crowd behaviour, changes to facility layout, or changes to management policies, could not only impact the actual Tawaf crowd but also impact pre- and post-Tawaf activities. When a pilgrim reaches Masjid al-Haram to perform the Tawaf ritual, they walk through the non-Tawaf waiting area, which includes the outside courtyard of Masjid al-Haram but also the prayer areas inside the Masjid al-Haram not used for Tawaf. As well, depending on the crowd already performing the Tawaf, the pilgrims who arrive may have to wait in the Tawaf waiting area before performing the Tawaf ritual. After potentially waiting in the Tawaf waiting area, the pilgrims proceed to the Tawaf area, which includes the main floor, second floor, or roof of the Masjid al-Haram. Once a pilgrim reaches the Tawaf area, they circumambulate the Kaaba seven times. After completing the Tawaf, the pilgrims proceed to the adjacent area in Masjid al-Haram to perform the Saee ritual. As such, the TawafDSS should consider modeling the Tawaf waiting area, the Tawaf ritual, and the post-Tawaf Saee ritual.

If the status quo Tawaf crowd management policies are significantly modified, then the Tawaf waiting area and the Tawaf area should both be modeled while the post-Tawaf Saee ritual need not be modeled. Any significant changes to the Tawaf crowd management policies are likely to make the Tawaf ritual the bottleneck, which will lead to a greater build up of pilgrims in the Tawaf waiting area. However, this bottleneck should not impact the Saee ritual as it already has a greater capacity then the Tawaf area. As such, any significant changes to Tawaf crowd management policies will impact the crowd dynamics in both the Tawaf waiting area and the Tawaf area but not the Saee ritual.

The ABMS is a better technique to model the Tawaf area then the QT technique. First, individual pilgrims influence the Tawaf crowd emergent behaviour. Second, for new Tawaf crowd management scenarios, the arrival and service distributions of the pilgrims are not known. As such, the ABMS technique is able to model the micro-level behaviour of the pilgrims and then simulates the emergent crowd movement better than QT technique, which is discussed in detail in Chapter 4.

The QT technique is a better technique to model the waiting time of the pilgrim in the Tawaf waiting area than the ABMS technique. First, the individual pilgrim behaviour does not significantly affect the crowd movements in the Tawaf waiting area since each pilgrim goes through the waiting area in roughly a first-come-first-served approach. Second, the arrival and service distributions can be obtained from the ABMS for the Tawaf area for each of the new Tawaf crowd management scenarios. As such, the QT technique is better to model the performance analysis of the Tawaf waiting area, which is discussed in detail in Chapter 5.

CHAPTER 4

TawafSIM: Tawaf ABMS Model

This chapter describes in detail the Tawaf ABMS called TawafSIM, which includes the discussions on its objective, implementation, simulation observations, validation, and results.

4.1 Objective

The objective of TawafSIM is to model the micro-level behaviour of Hajj pilgrims performing the Tawaf ritual in order to explore the impact of crowd characteristics, facility layout, and management decisions on emergent crowd behaviour and Tawaf performance during the complex crowd movements. The next two subsections describe the Tawaf modeling requirements and the Tawaf modeling philosophy used to implement TawafSIM.

4.1.1 Tawaf Modeling Requirements

To meet the above objective, TawafSIM should model a minimum set of features. First, it should model pilgrim characteristics for gender, manners, speed, strength, desires, and health. Second, it should be able to modify the number of entry points into the Tawaf area. Third, it should model management policies for pilgrim rate of entry and maximum pilgrim capacity. As such, TawafSIM will be able to explore the impact of crowd characteristics, facility layout, and management decisions on Tawaf performance.

As well, TawafSIM should measure a minimum set of Tawaf performance metrics. First, throughput should measure number of pilgrims completing Tawaf per hour. Second, satisfaction should measure how satisfied the pilgrims are with the Tawaf experience. Third, health should measure how exposed susceptible pilgrims are to infecting pilgrims. Finally, safety should measure the safety level during the Tawaf. As such, these four metrics should help determine the overall Tawaf performance.

Finally, although it is difficult to get officially published Tawaf data, TawafSIM should meet the following Tawaf constraints. First, although the official number of pilgrims in the 2011 Hajj year is 2.8 million, it is estimated the actual number of pilgrims is closer to 4.0 million due to the large number of unauthorized pilgrims performing Hajj. Second, the ideal duration to perform the Tawaf during Hajj is 24 hours, but practically, the target has been closer to 48 hours for the past several years with some scholars holding the opinion it could be extended to 72 hours. Third, the Tawaf is most challenging on the main courtyard, which is estimated to represent either one quarter or one third of the total Tawaf area (i.e. courtyard, second floor, and roof). As such, TawafSIM should ensure one third of the 4.0 million pilgrims can perform Tawaf during 48 hours within the one third Tawaf area represented by the courtyard.

4.1.2 Tawaf Modeling Philosophy

To make significant improvements to the Tawaf performance, instead of modeling and simulating the status quo with its well-known undesirable and avoidable Tawaf crowd dynamics that cause significant negative impact to Tawaf performance, pragmatic new Tawaf policies that eliminate the negative crowd dynamics should be modeled and simulated to find the optimum crowd management decisions as was successfully done recently with the Jamarat ritual.

The Jamarat ritual recently made significant crowd performance improvements by eliminating well-known undesirable crowd dynamics that previously resulted in a large number of deaths and injuries through new crowd behaviour, facility design, and management polices, which were then modeled and simulated [15] to find optimum crowd management decisions. First, each of the three pillars at the old Jamarat site used to attract a high-density crowd. To eliminate the high-density crowd, the pillar was replaced with a lengthy wall, which significantly dispersed the crowd. Second, the facility design at the old Jamarat site used to result in head on opposing pilgrim traffic with the highest crowd densities possible when pilgrims were arriving and departing at the pillars. Redesigning the new Jamarat site to have crowds move through a one-way path eliminated this situation. To further ensure everyone followed the new rules, a schedule was established to visit the Jamarat and a significant military presence was placed at the entrance to the new Jamarat site to serve as a visible deterrent to those thinking of not following the new rules. Once the new rules were established, in subsequent years, the military presence was removed. As such, rather than simulate the status quo crowd behaviour, facility design, and management policies of the old Jamarat site to find marginal aspects to improve, the Jamarat simulation was of the new crowd behaviour, facility design, and management policies, which led to massive improvement to the Jamarat crowd performance.

Similarly, the well-known undesirable and avoidable Tawaf crowd dynamics, which are linked to the disturbance to the natural circular Tawaf crowd flow and high crowd density, can be replaced with pragmatic new crowd behaviour, facility design, and management polices, then modeled and simulated to find optimum crowd management decisions. First, the most significant source of this disturbance is the constant formation of a mob of pilgrims at the Black Stone, who struggle among themselves to touch the Black Stone. This mob causes a significant disturbance to the natural flow of the crowd as it moves across the Tawaf line, which stretches from the Kaaba corner to approximately thirty feet away. The crowd closest to this mob faces a restricted path to their natural trajectory and as a consequence are squeezed together and propelled forward for ten or more feet resulting in significant pushing against each other as the crowd attempts to remain on its feet while moving past the mob. Although only approximately half of one percent of the total number of pilgrims attempts to touch the Black Stone, this constant mob continuously causes extreme hardship for a large percentage of the pilgrims. The second source of disturbance to the naturally circular Tawaf crowd is due to the crowd circling the Kaaba structure that is rectangular shaped, which causes a crowd density build up on the sides of the Kaaba starting with the Black stone and continuing until the opposite side is reached [37]. Although this disturbance is not as acute as the mob at the Black Stone, it impacts half of the Tawaf courtyard [21]. The third source of disturbance, which causes significantly less negative impact on the crowd dynamics, is the crowd of pilgrims touching the three sides of the Kaaba wall, which are accessible to pilgrims. A final condition that contributes negatively to the Tawaf performance is the extreme high density of pilgrims. This high density not only negatively impacts safety, satisfaction, and health, but it also ironically negatively impacts throughput. According to [21], at these extreme crowd densities, typical round completion time on the roof is faster than at the courtyard even though the roof has a significantly larger distance to cover per round. As such, since the source of the three negative impacts to the Tawaf performance are known, these status quo negative crowd dynamics should be eliminated to bring significant improvement to the Tawaf performance.

Simple pragmatic policies exist to eliminate the disturbance to the natural flow of Tawaf crowd movement and high crowd density. First, a pragmatic facility design-based policy is to place a temporary circular barrier around the Kaaba. This would eliminate all three sources of the disturbances. In fact, such a barrier is used on the first day of Hajj when all the pilgrims have moved to Mina. The objective of the barrier is to allow workers to change the Kaaba outer covering without interference from the crowd performing voluntary Tawaf. The only objection to this solution could be that placing a barrier around the Kaaba and preventing people from approaching the Kaaba is prohibited or to a lesser degree disliked religiously. However, if the religious scholars determine that the small numbers of pilgrims who are performing a recommended act of worship are causing harm to a large number of pilgrims performing the obligatory act of worship, perhaps the circular barrier will be adopted, as was the adoption of removing the Tawaf start line and changing the Jamarat pillars to walls. As such, a complete circular barrier (similar to the semi-circular barrier at one side of the existing Kaaba) placed around the Kaaba during only the Tawaf Ifadah to allow the 4.0 million pilgrims to perform the obligatory Tawaf in the 48-hour period should result in superior Tawaf performance. Second, to eliminate the obvious high-density crowds while still achieving the required throughput to get all 4.0 million pilgrims to perform Tawaf during the 48 hours is to find the lowest crowd density that still achieves the required throughput. These common sense inspired changes would impact crowd behaviour, facility design, and management preference that should significantly help create better Tawaf conditions with respect to throughput, satisfaction, health, and safety.

Consequently, rather than model the status quo Tawaf crowd behaviour, facility design, and management policies with there well-known issues that may help discover marginal improvements in the Tawaf crowd performance, it is better to model and simulate the new proposed crowd behaviour, facility design, and management policies that eliminate the well-known undesirable Tawaf crowd dynamics to find the management decisions leading to massive improvement to the Tawaf crowd performance as was accomplished recently for the Jamarat ritual.

4.2 Implementation

This section begins with a brief discussion of whether to implement TawafSIM using custom software code, generic ABMS software package, or generic pedestrian modeling software. It then continues the discussion with: (i) assumptions made; (ii) modelling Tawaf courtyard, pilgrim attributes, and pilgrim behaviour; (iii) measuring throughput, satisfaction, health, and safety; and (iv) program flow and key methods.

4.2.1 Custom versus Generic Tawaf Simulator

It is better to develop a custom ABMS simulator for the Tawaf crowd model rather than modify a generic ABMS simulator or generic pedestrian simulator. First, a generic open source ABMS simulator like Repast [32] has the advantage of quick, easy, and extendable software development of a crowd simulator using a proven ABMS environment. However, the drawback is Repast does not have specialized pedestrian modeling capability pre-built into it. Furthermore, since the Tawaf has specific crowd movement behaviour, Repast would limit the degree of functionality and metrics that could be developed into a Tawaf simulator.

Second, a generic pedestrian simulator like Legion [24] has the advantage of a specialized pedestrian simulation environment with a proven track record. However, the drawbacks are it is not built on the natural ABMS approach and it is not easily modified since it is not open source. As well, the Tawaf simulation would be limited to the functionality of the existing pedestrian capability.

Third, a custom Tawaf simulator would have the advantage of full flexibility to design the simulator using ABMS approach with pedestrian features specific for the Tawaf. However, the drawback is the complexities to develop the simulator from scratch, the length of time to build it, and the lack of resources to build all the features of existing pedestrian simulators.

Finally, Sarmady et al. [34] provide an evaluation of software modeling packages to simulate the Tawaf crowd in which they conclude building custom simulation software for the Tawaf is the only alternative. Interestingly, their later work in [33, 35] to model the Tawaf crowd uses a generic tool perhaps in order to quickly develop the model but at the expense of being limited to features provided by the generic tool. Consequently, if the state-of-the-art in Tawaf crowd simulator is desired both generic ABMS software and generic pedestrian software will not be adequate. Thus, the Tawaf simulator should be developed as a custom software, which will require significantly more time and resources to develop but with the full flexibility to design a specialized simulator specifically for the Tawaf ritual.

4.2.2 Modelling Assumptions

The Tawaf ABMS makes several assumptions. First, it assumes the circular barrier solution to the well-known negative crowd dynamics is religiously acceptable. Therefore, the mob at the Black Stone is not modeled nor is the crowd around the Kaaba walls. Second, since the Abraham station is approximately five by five feet, we assume that the crowd can easily disperse itself around it without significant impact on the throughput, satisfaction, health, and safety. Third, only the Tawaf courtyard is modeled, although extending the model for the other areas is straightforward. Fourth, pilgrims maintain a minimum 1 step per second pace unless all next step locations are occupied, in which case the pilgrim pauses for that time step.

4.2.3 Modelling: Tawaf Courtyard

Although the Tawaf can occur on the main courtyard, second floor, and roof of Masjid al-Haram, only the courtyard is being modeled since it is the most challenging Tawaf area.

4.2.3.1. Courtyard Shape & Size

According to [37], the courtyard is 164 by 104 meters (538.1 by 341.2 feet) with the Kaaba building approximately in the center of the courtyard with dimensions of 11 by 12 meters (36.1 by 39.4 feet), which does not include the Hateem (semi-circular closed area directly in front of the Kaaba building), which is also part of the Kaaba. TawafSIM models the Tawaf courtyard area as a circle with 39.6 m (130 feet) radius with the Kaaba at the center of the circle. Since it is assumed that the Kaaba will be completely surrounded with a temporary barrier as there is around the Hateem, the minimum and maximum Tawaf radius is 11.3 m (37 feet) and 39.6 m (130 feet) respectively. The remaining part of the courtyard is not modeled to leave room for pilgrims entering and exiting the courtyard and also to prevent the non-circular part of the courtyard from generating resistance to the circular movement of the crowd, which would decrease throughput [37]. As a comparison, the Tawaf crowd models in [37] and [1] model the maximum Tawaf courtyard radius to be 48 meters (157.5 feet).

4.2.3.2. Courtyard Grid Resolution

The Tawaf ABMS courtyard is modeled at a 1 by 1 foot grid resolution, where only one pilgrim can occupy a single grid at a time. Since the new Tawaf crowd management policy will cap the number of pilgrims in the Tawaf area to a number that will not result in gridlock while allowing all the pilgrims to finish the Tawaf during the 48-hour time limit, a 1 by 1 foot resolution will be adequate. On the other hand, if the status quo high crowd densities leading to gridlock and low throughput were to be modeled, it would imply that the pilgrims may be inching their way forward at times, which would require the courtyard to be modeled at a theoretically finer resolution, such as 5 by 5 cm (0.2 by 0.2 feet) as in [36]. Since the theoretically finer resolution would involve significant more computation time, it is replaced with the more pragmatic 40 by 40 cm (1.3 by 1.3 feet) resolution as in [33, 35, 37]. In [39] a 10 by 10 cm (0.3 by 0.3 feet) resolution is chosen primarily to accommodate the close packing of people as they inch forward at times to enter and exit sport facilities to study the impact on pedestrian safety and evacuation scenarios.

4.2.4 Modelling: Pilgrim Attributes

The attributes of the agents in the ABMS define what the pilgrim is, which includes its: id, size, gender, manners, speed, strength, health, and desire to touch Kaaba (Black Stone).

Each pilgrim in TawafSIM is modeled as a 1 by 1 foot square shape, which is also the resolution of the Tawaf courtyard. This pilgrim size and shape intuitively represents the smallest space that most people may be forced to assume, which is consistent with [18] where Hajj crowd density can reach up to 9 people per square meter (7.5 people per 9 ft^2). As well, there is significant discussion [39] on the correct anthropomorphically representation of the wide range of human body shapes, which is determined to be 50 by 30 cm (1.6 by 1.0 feet); however, a 30 by 30 cm (1.0 by 1.0 feet) equivalent square is used instead for computational simplicity to represent the area of the shape. Additionally, the maximum body depth of 35 cm (1.1 feet) and breadth of 54 cm (1.8 feet) along with Muslim bodies sizes are listed in [4]. Finally, in [36] 40 by 40 cm (1.3 by 1.3 feet) was used to model a pilgrim, which matched their courtyard grid resolution.

In TawafSIM, each pilgrim has low, medium, and high states for its manners, strength, and desire to touch Kaaba (Black Stone) attributes, which along with its gender attribute influences its movement while it circumambulates the Kaaba seven times. Other than gender, these attributes are difficult to infer for the pilgrim population but can be approximated using a pre- or post-pilgrim survey and observations.

The maximum speed attribute of a pilgrim is modeled to be 0.30, 0.61, and 0.91 m/s (1, 2, or 3 feet per second), which is based on measuring a range of people walking while pretending to perform the Tawaf. The maximum 0.3 m/s (1-foot per second) speed generally represents a pilgrim with slow walking speed due to age, fatigue, or other hardship. The maximum 0.61 m/s (2-feet per second) speed generally represents a typical healthy pilgrim concentrating on the act of worship during the Tawaf. While the maximum 0.91 m/s (3-feet per second) speed generally represents a pilgrim concentrating more on finishing the Tawaf and less on the act of worship. There is significant discussion and difference of opinion on what the speed of a pedestrian should be for different walking scenarios. As a comparison, [4] measured walking speed as 0.89, 0.67, and 0.53 m/s (2.92, 2.19, and 1.73 feet per second) as high, medium, and low speeds respectively. While in [5], walking speed is reported to be 1.17 and 1.1 m/s (3.84 and 3.64 feet per second) for men and women respectively. Finally, the Tawaf model in [1] uses 0.50 and 1.00 m/s (1.64 and 3.28 feet per second) for slow and fast pilgrim velocities respectively.

The infected, immune, or susceptible states of a pilgrim's health attribute help determine how infectious diseases can spread from pilgrim to pilgrim during the Tawaf. The percentage of pilgrim population, which is infected, immune, and susceptible during the

Tawaf have to be estimated using a post-Hajj pilgrim questionnaire and also information from the Hajj medical record system.

4.2.5 Modelling: Pilgrim Behaviour

The behavioural characteristics of the ABMS define what the pilgrim does, which includes: (i) perceive surrounding Tawaf courtyard environment; (ii) evaluate goals for number of rounds to spiral in, maintain circle, and spiral out based on attributes and environment; (iii) evaluate next step movement destination for macro-level trajectory using spiral-based equation then micro-level refinements in movement by evaluating fitness of each Moore neighbour of macro-level destination where the Moore neighbours are the eight cells surrounding a central cell in a square grid; (iv) select best next step movement location using decision rules; and (v) adapt new macro spiralling trajectory based on past experience.

4.2.5.1. Perceive Surrounding Environment

Each pilgrim constantly monitors the environment. First, the pilgrim is always aware of its location in both the Cartesian (x & y point) and Polar (radius & θ) coordinate systems, where the Kaaba is at the origin. Second, the pilgrim is aware of the courtyard landmarks, which include: current crowd boundary, Tawaf start line, and Kaaba perimeter. Third, the pilgrim is aware of the number and the gender of its Moore neighbours.

4.2.5.2. Evaluate Movement Options using Internal Models

The movement of each pilgrim is controlled by both macro- and micro-level movement mechanisms based on the pilgrim's attributes and the Tawaf crowd environment.

The macro-level movement uses a spiral equation to determine the ideal trajectory of the pilgrim while spiralling inward to get closest to the Kaaba in the first few rounds, holding this radius by circling for a few more rounds, and then spiralling outward in the last few rounds to exit the Tawaf crowd. The spiral equation is an ideal macro-level mechanism because it allows a wide range of Tawaf round trajectories to be modeled based on its starting and ending Polar coordinates. As such, each pilgrim can determine its distinct macro-level path by using its starting position (radius & angle) and desired number of rounds to spiral in, maintain, and spiral out, which are based on the pilgrim's attributes.

If there were no other pilgrims making Tawaf, the macro-level spiral equation would be sufficient to provide the movement mechanism. However, to avoid collision with other pilgrims and avoid other crowd conditions due to personal preferences, a micro-level mechanism based on evaluating the fitness of each Moore neighbour of the macro-level destination is used.

The macro- and micro-level movement mechanisms are able to model a range of pilgrim movements based on their attributes. For instance, a pilgrim with low manners is more likely to be inconsiderate to other pilgrims while moving through the courtyard by setting spiral inward and choosing next step position that meet their own goals without considering how it impacts other pilgrims. In particular, the manners of each pilgrim help set the spiral inward goal of the pilgrim while circumambulating the Kaaba seven times. In general, if a low mannered pilgrim wanted to spiral inwards towards the Kaaba and the crowd density was high, then the pilgrim would still set its goal to spiral inward whereas a high mannered pilgrim who also desired to spiral inward would not set its goal to spiral inward as much when the crowd density was high because it would inconvenience others. Similarly, manners also influence the next step position. A low mannered pilgrim would move to the next step position that was most suitable for the pilgrim whereas the pilgrim with the high manners will take into consideration how its actions will impact others by looking at the number of total and opposite gender pilgrims around it. Similar impact occurs due to pilgrim strength and desire to touch Kaaba (Black Stone).

As such, the combination of macro- and micro-level movement mechanisms allow the pilgrim to: (i) perform simple calculations to provide spiral in, maintain circle, and spiral out Tawaf movement; (ii) avoid collisions; (iii) accommodate personal congestion avoidance decisions; and (iv) provide distinct movement patterns based on pilgrim attributes and local environment conditions. For comparison, the Tawaf crowd model in [37] used a discrete event model to simulate actions and behaviours while in [39] model parameter calibration is used to provide movements using cellular automata.

4.2.6 Measuring: Throughput, Satisfaction, Health, & Safety

Most crowd models focus on understanding safety and evacuation dynamics. Even the Tawaf crowd models focus on throughput and safety. As well, some emphasize the animation of the simulation result. TawafSIM does not rely solely on the crowd dynamic animation as it provides limited information; instead it develops a comprehensive set of metrics to measure the performance of crowds in general and in particular Tawaf performance, which includes throughput, safety, satisfaction, and health.

4.2.6.1. Throughput Metrics

Throughput metric for the Tawaf model measures the number of pilgrims who complete the Tawaf per unit time, which is based on the time it takes to complete each of the seven rounds. Since the pilgrims spiral in for the first few round, then maintain a circle pattern for few rounds, and finish by spiralling out in the last few rounds, the time to complete each round is different because of the distance and congestion levels at the different radii. Therefore, it is not only useful to measure the throughput of the system, but it is more insightful to understand the impact of the time to complete each round on the throughput. Consequently, the throughput metric measures the average time to complete each round.

4.2.6.2. Satisfaction Metrics

TawafSIM is the only crowd model that uses three complementary satisfaction metrics specific to the Tawaf. First, the percentage of time a pilgrim is off the desired spiral path measures how often the pilgrim has to readjust its macro-level trajectory due to avoiding a collision or other undesirable crowd congestion situation. As such, rather than concentrating on the act of worship, the pilgrim spends time to correct its trajectory. Second, the percentage of time with 0 to 8 neighbours shows how much congestion the pilgrim experiences in its Moore Neighbourhood during the Tawaf. As the level of congestion increases, it generally decreases the level of concentration on acts of worship. Third, the percentage of time with 0 to 8 opposite gender neighbours shows how much time a pilgrim becomes an immediate neighbour to the opposite gender. Since opposite genders from outside the immediate family should not come in contact with each other, the number should be as close to zero as possible. Therefore, these three metrics should give a good indication about the level of satisfaction the pilgrim experiences during the Tawaf, which can be confirmed in the future with the use of pre- and post-Hajj pilgrim surveys.

4.2.6.3. Health Metrics

It is a well-known fact that the spread of infectious diseases is a concern at MGs, including the Hajj. When a large crowd has to be in close proximity with each other, it increases the chances of spreading infectious diseases [19]. As such, TawafSIM tracks what percent of the pilgrim's Tawaf duration is spent with infecting pilgrims. The greater the amount of time with infecting people, the greater the chance a healthy pilgrim who has not been immunized for the infectious disease will get infected. As such, the health metric provides an insight into the spread of infectious diseases.

4.2.6.1. Safety Metrics

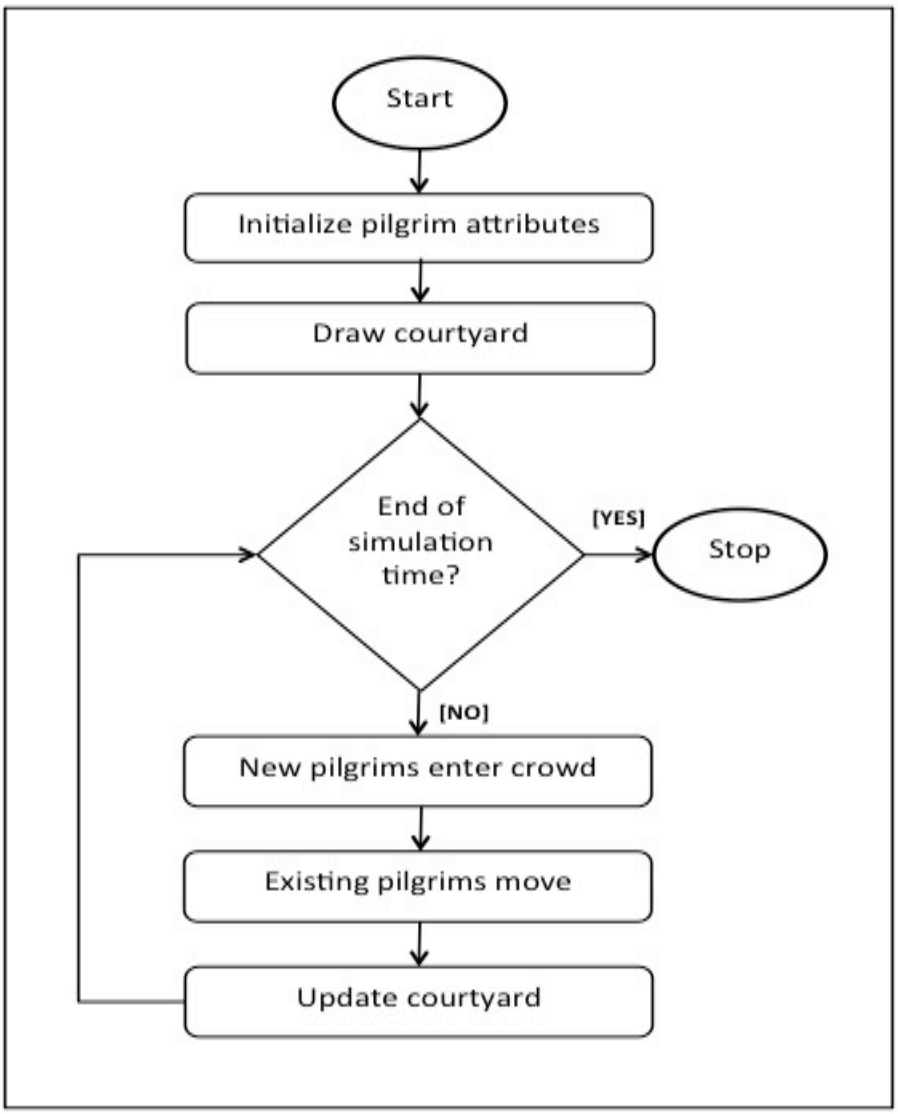
Although safety is a concern for pedestrian crowds, there is no consensus on what is a safe level of people per unit space to prevent casualties from crush and stampede conditions. In [33] it is reported that it is unsafe above 4 people per square meter (3.3 people per 9 ft^2) while in [21] it is 6 persons per square meter (5.0 people per 9 ft^2). As well, other than this perception of people per unit space, there is no other safety metric defined or measured.

TawafSIM uses three safety metrics, which help management to better understand how crowd behaviour, design layout, and management preferences affect safety conditions during the Tawaf. First, the Tawaf crowd of maximum 39.6 m (130 feet) radius is placed in the center of a 91.4 by 91.4 m (300 by 300 feet) courtyard. Second, the courtyard area is divided into 100 safety grids of 9.1 by 9.1 m (30 by 30 feet). Third, low, medium, and high threat levels for these safety grids are defined respectively as: (i) fewer than 200 pilgrims (2 pilgrims/Moore neighbourhood); (ii) between 200 to 400 pilgrims (2 to 4 pilgrims/Moore neighbourhood); and (iii) greater than 400 pilgrims (4 pilgrims/Moore neighbourhood). Note the Moore neighbourhood is 0.8 m^2 (9 square feet) since each cell is 0.3 by 0.3 m (1 by 1 foot). Fourth, the percentage of courtyard grids that are in low, medium, and high threat levels during the simulation are measured, which shows how the threat levels change with time and how wide spread is the high threat level. Fifth, the highest density values per grid shows the highest density per Moore neighbourhood for each grid attained during the simulation, which identifies the courtyard locations with the highest density. Sixth, the percent of time in high threat per grid shows how often each grid remains in the high threat conditions, which is important to determine how serious is the situation. Therefore, the safety metrics provide significant insight into the safety situation during the Tawaf.

4.2.7 Program Flow & Key Methods

Figure 10 shows how the TawafSIM starts by initializing attributes of all the pilgrims and drawing the empty courtyard grid with the Kaaba in the center with its circular boundary. Next the ABMS program simulates 1-second time steps until the maximum simulation time is reached. Every second, (i) new pilgrims can enter the Tawaf crowd, (ii) each pilgrim already in the Tawaf crowd can move to its next position using asynchronous position updating, and (iii) the grid is updated with the next position of every pilgrim in the Tawaf crowd. Finally, after the maximum simulation time is reached, the Tawaf performance metric data is saved to a file. The key methods are further explained.

Figure 10: TawafSIM program flowchart



4.2.7.1. Pilgrim Population is Initialized

The method *initAgents()* assigns each pilgrim being simulated with its distinct attributes: id, gender, manners, speed, strength, health, and desire to touch Kaaba (Black Stone). The distributions for the attributes are discussed in subsection 4.3 Simulation Observations, which are based on reasonable estimates (all micro-simulation Tawaf models [1, 12, 37] have used estimates for attribute) until this data is collected and made available by the Hajj authorities. Although as discussed, a post-Hajj pilgrim questionnaire along with Hajj records could provide better estimates. Nevertheless, the ability to vary the distributions of these attributes provides invaluable information to better understand how pilgrim attributes impact Tawaf performance metrics for throughput, satisfaction, health, and safety.

4.2.7.2. Pilgrims Enter Tawaf Crowd

At the beginning of every time step, the method *agentsEnterTawafCrowd()*, may allow a number of new pilgrims to enter the Tawaf crowd, which is the lesser of either the management set pilgrim entry rate or number of pilgrims to reach the management set maximum pilgrim capacity for the courtyard.

For each new pilgrim entering the crowd, the pilgrim's behavioural spiralling goals are set after the pilgrim is randomly placed on the edge of the current Tawaf crowd boundary. First, of the total seven rounds in the Tawaf, the number of rounds to: (i) spiral inward to get closest to the Kaaba, (ii) circle to maintain distance to Kaaba after spiralling inward, and (iii) spiral outward to reach the crowd boundary are set, which are a function of the pilgrim's strength, manners, speed, gender, and desire to touch Kaaba

(Black Stone). The number of rounds to spiral inward is 1 to 4, the number of rounds to maintain constant circle after spiralling in is 4 to 1, and the number of rounds to spiral out is 2. In general, high strength, low manners, high speed, high desire to touch Kaaba (Black Stone), and men are going to have a smaller number of rounds to spiral in and a larger number of rounds to maintain constant circle since they are more aggressive to reach the closest distance to the Kaaba and maintain their position. Second, the closest distance to the Kaaba to reach after the spiral inward is also determined, which is a function of the current Tawaf crowd boundary and the spiral inward number of rounds. In general, the smaller the number of rounds to spiral inward, the closer the distance to the Kaaba is set because again they represent the most aggressive pilgrims. Third, the Cartesian and Polar coordinates of the pilgrim's location are determined, and the pilgrim is placed on the grid.

After all the new pilgrims enter the crowd, it is determined whether the crowd boundary needs to be expanded, which occurs when the last incremental crowd boundary is approximately one-third full.

4.2.7.3. Pilgrims Move To Next Position

Each time step, after any new pilgrims enter the Tawaf crowd, the method *agentsMoveSpiral()*, moves each pilgrim in the Tawaf crowd to its next position. This involves: (i) removing pilgrim from its current grid location, (ii) finding its next position, (iii) assigning pilgrim to its new grid location, (iv) determining if a round has completed, and (v) determining if the number of rounds for spiral inward, constant circling, or spiral outward have finished.

The *findBestPosition()* procedure is further explained, which determines the next best position for a pilgrim. A spiral equation provides a macro-movement trajectory while the micro-level movement is based on selecting the most appropriate next position in its Moore neighbourhood. First, the Polar coordinate system is used to calculate the new θ value, $\theta_{new} = \theta_{current} - (v/r_{current})$, which is a function of the current radius of the pilgrim and the pilgrim's speed. Second, the new radius value is calculated using the new θ value in the spiral equation, $r_{new} = r_{initial} b^{\theta_{new}}$ where $b = e^{\ln(r_{final})/\theta_{final}}$. Third, of the 8 next step locations in a pilgrim's Moore neighbourhood, only the top 5 positions, which take the pilgrim toward the spiral equation location five-time steps later, are selected. Fourth, for each of these top 5 ranked positions in its Moore neighbourhood, a next position selection value is assigned to it, which is a function of: (i) rank number of the position, (ii) number of total Moore neighbours for the position, and (iii) number of opposite gender Moore neighbours for the position. If all the next positions are occupied, then the pilgrim does not move for that time step; otherwise, it moves to the position corresponding to the lowest value next position selection value.

4.3 Simulation Observations

TawafSIM is used to simulate a set of 42 scenarios (Figure 11), which includes a default scenario with typical simulation parameters along with an additional twelve categories of scenarios testing the impact of pilgrim behaviour (i.e. gender, manners, speed, strength, desire to touch Kaaba/Black Stone, immunization/infecting, and degree of spiral inward), facility design (i.e., circular courtyard entry access), and management preference (i.e.,

Figure 11: TawafSIM simulation scenario parameters

SCENARIO	GENDER		RATE OF ENTRY	ENTRY ACCESS	MAX PILGRIMS	MANNERS			SPEED			STRENGTH			DESIRE TOUCH			HEALTH			SPIRAL IN THRESHOLDS		
[#]	[% Male]	[% Female]	[Pilgrims/sec]	[Degrees]	[#]	[% Low]	[% Med]	[% High]	[% Low]	[% Med]	[% High]	[% Low]	[% Med]	[% High]	[% Low]	[% Med]	[% High]	[% Immunized]]	[% Susceptible]	[% Infecting]	[Round 1]	[Round 2]	[Round 3]
1	60	40	20	360	25000	25	50	25	25	50	25	25	50	25	25	50	25	20	50	30	0.24	0.33	0.42
2	100	0	20	360	25000	25	50	25	25	50	25	25	50	25	25	50	25	20	50	30	0.33	0.39	0.45
3	75	25	20	360	25000	25	50	25	25	50	25	25	50	25	25	50	25	20	50	30	0.28	0.36	0.42
4	25	75	20	360	25000	25	50	25	25	50	25	25	50	25	25	50	25	20	50	30	0.21	0.27	0.34
5	0	100	20	360	25000	25	50	25	25	50	25	25	50	25	25	50	25	20	50	30	0.18	0.24	0.30
6	60	40	10	360	25000	25	50	25	25	50	25	25	50	25	25	50	25	20	50	30	0.24	0.33	0.42
7	60	40	15	360	25000	25	50	25	25	50	25	25	50	25	25	50	25	20	50	30	0.24	0.33	0.42
8	60	40	25	360	25000	25	50	25	25	50	25	25	50	25	25	50	25	20	50	30	0.24	0.33	0.42
9	60	40	300	360	25000	25	50	25	25	50	25	25	50	25	25	50	25	20	50	30	0.24	0.33	0.42
10	60	40	600	360	25000	25	50	25	25	50	25	25	50	25	25	50	25	20	50	30	0.24	0.33	0.42
11	60	40	900	360	25000	25	50	25	25	50	25	25	50	25	25	50	25	20	50	30	0.24	0.33	0.42
12	60	40	20	90	25000	25	50	25	25	50	25	25	50	25	25	50	25	20	50	30	0.24	0.33	0.42
13	60	40	20	180	25000	25	50	25	25	50	25	25	50	25	25	50	25	20	50	30	0.24	0.33	0.42
14	60	40	20	270	25000	25	50	25	25	50	25	25	50	25	25	50	25	20	50	30	0.24	0.33	0.42
15	60	40	20	360	30000	25	50	25	25	50	25	25	50	25	25	50	25	20	50	30	0.24	0.33	0.42
16	60	40	20	360	35000	25	50	25	25	50	25	25	50	25	25	50	25	20	50	30	0.24	0.33	0.42
17	60	40	20	360	40000	25	50	25	25	50	25	25	50	25	25	50	25	20	50	30	0.24	0.33	0.42
18	60	40	20	360	25000	100	0	0	25	50	25	25	50	25	25	50	25	20	50	30	0.32	0.39	0.45
19	60	40	20	360	25000	0	100	0	25	50	25	25	50	25	25	50	25	20	50	30	0.25	0.33	0.40
20	60	40	20	360	25000	0	0	100	25	50	25	25	50	25	25	50	25	20	50	30	0.20	0.27	0.40
21	60	40	20	360	25000	25	50	25	100	0	0	25	50	25	25	50	25	20	50	30	0.20	0.27	0.35
22	60	40	20	360	25000	25	50	25	0	100	0	25	50	25	25	50	25	20	50	30	0.25	0.33	0.40
23	60	40	20	360	25000	25	50	25	0	0	100	25	50	25	25	50	25	20	50	30	0.31	0.39	0.46
24	60	40	20	360	25000	25	50	25	25	50	25	100	0	0	25	50	25	20	50	30	0.20	0.27	0.34
25	60	40	20	360	25000	25	50	25	25	50	25	0	100	0	25	50	25	20	50	30	0.25	0.33	0.40
26	60	40	20	360	25000	25	50	25	25	50	25	0	0	100	25	50	25	20	50	30	0.31	0.39	0.46
27	60	40	20	360	25000	25	50	25	25	50	25	25	50	25	100	0	0	20	50	30	0.19	0.28	0.35
28	60	40	20	360	25000	25	50	25	25	50	25	25	50	25	0	100	0	20	50	30	0.24	0.33	0.40
29	60	40	20	360	25000	25	50	25	25	50	25	25	50	25	0	0	100	20	50	30	0.29	0.38	0.45
30	60	40	20	360	25000	25	50	25	25	50	25	25	50	25	25	50	25	20	70	10	0.24	0.33	0.42
31	60	40	20	360	25000	25	50	25	25	50	25	25	50	25	25	50	25	20	60	20	0.24	0.33	0.42
32	60	40	20	360	25000	25	50	25	25	50	25	25	50	25	25	50	25	20	40	40	0.24	0.33	0.42
33	60	40	20	360	25000	25	50	25	25	50	25	25	50	25	25	50	25	20	30	50	0.24	0.33	0.42
34	60	40	20	360	25000	25	50	25	25	50	25	25	50	25	25	50	25	0	70	30	0.24	0.33	0.42
35	60	40	20	360	25000	25	50	25	25	50	25	25	50	25	25	50	25	10	60	30	0.24	0.33	0.42
36	60	40	20	360	25000	25	50	25	25	50	25	25	50	25	25	50	25	30	40	30	0.24	0.33	0.42
37	60	40	20	360	25000	25	50	25	25	50	25	25	50	25	25	50	25	40	30	30	0.24	0.33	0.42
38	60	40	20	360	25000	25	50	25	25	50	25	25	50	25	25	50	25	50	20	30	0.24	0.33	0.42
39	60	40	20	360	25000	25	50	25	25	50	25	25	50	25	25	50	25	20	50	30	0.00	0.00	0.00
40	60	40	20	360	25000	25	50	25	25	50	25	25	50	25	25	50	25	20	50	30	0.00	0.00	1.00
41	60	40	20	360	25000	25	50	25	25	50	25	25	50	25	25	50	25	20	50	30	0.00	1.00	0.00
42	60	40	20	360	25000	25	50	25	25	50	25	25	50	25	25	50	25	20	50	30	1.00	0.00	0.00

NOTES: (1) Scenario 1 is the default values for all the simulation parameters, which represent typical conditions for the Tawaf.
(2) Scenarios 2 to 5 test the impact of gender distribution.
(3) Scenarios 6 to 8 test the impact of the constant rate of pilgrim entry.
(4) Scenarios 9 to 11 test the impact of the burst duration in seconds for bursty rate of pilgrim entry cycling between 15, 25, and 35 pilgrims/sec.
(5) Scenarios 12 to 14 test the impact of the pilgrims entering from a circular entry access limited to 90, 180, and 270 degrees respectively.
(6) Scenarios 15 to 17 test the impact of the maximum pilgrim capacity.
(7) Scenarios 18 to 20, 21 to 23, 24 to 26, and 27 to 29 test the impact of low, medium, and high levels of pilgrim manners, speed, strength, and desire to touch the Kaaba/Black Stone respectively.
(8) Scenarios 30 to 33 test the impact of the percentage of infecting pilgrims have on the susceptible pilgrim population given a fixed herd immunization level.
(9) Scenarios 34 to 38 test the impact of the herd immunization level on the susceptible pilgrim population given a fixed percentage of infecting pilgrims.
(10) Scenarios 39 to 42 test the impact of the three Spiral In simulation threshold values, which control the degree of spiral inward for rounds 1, 2, and 3 respectively.

rate of pilgrim entry and maximum pilgrim capacity in courtyard) on Tawaf performance metrics for throughput, satisfaction, health, and safety.

Scenario 1 is the default scenario with the most likely values for the ten parameters. Scenarios 2 to 5, look at the impact of gender. Scenarios 6 to 11 look at the impact of rate of pilgrim entry, which is given in pilgrims/second. In particular, 6 to 8 look at a constant rate of pilgrims while for 9 to 11 the number represents the pilgrim burst interval. Scenarios 12 to 14 look at the impact of the number of courtyard entry points, where an entry point covers a quarter of the courtyard. Scenarios 15 to 17 look at the impact of maximum allowed crowd in the courtyard. Scenarios 18 to 20, 21 to 23, 24 to 26, and 27 to 29 look at the impact of manners, speed, strength, and desire to touch the Kaaba/Black Stone respectively. Scenarios 30 to 38 look at the impact of immunization and infecting levels. Finally, scenarios 39 to 42 look at the impact of degree of pilgrim spiralling inward.

The following two subsections discuss the preliminary observations from the original TawafSIM generated data and the detailed observation from the data analysis of the generated data.

4.3.1 Observations from TawafSIM Generated Data

Each scenario is run for 7,200 seconds or until 90,000 pilgrims enter the Tawaf area, whichever comes first. Each scenario takes less than 10 minutes of real time to simulate 2 hours. The scenarios are run five times each to get average values for the Tawaf performance metrics, throughput, satisfaction, health, and safety, which are all within 2 percent from the average. The Tawaf performance metric plots are generated from the simulation data once the Tawaf courtyard has reached its maximum pilgrim capacity of 25,000 or as indicated in scenarios 15 to 17. Figures 12 to 17 show the default scenario simulation as snapshots with 5-minute intervals where red, green, blue, black, and yellow pilgrim colours are for spiralling in, no spiral, spiral out, last round, and distracted respectively.

Figure 12: TawafSIM snapshot 1

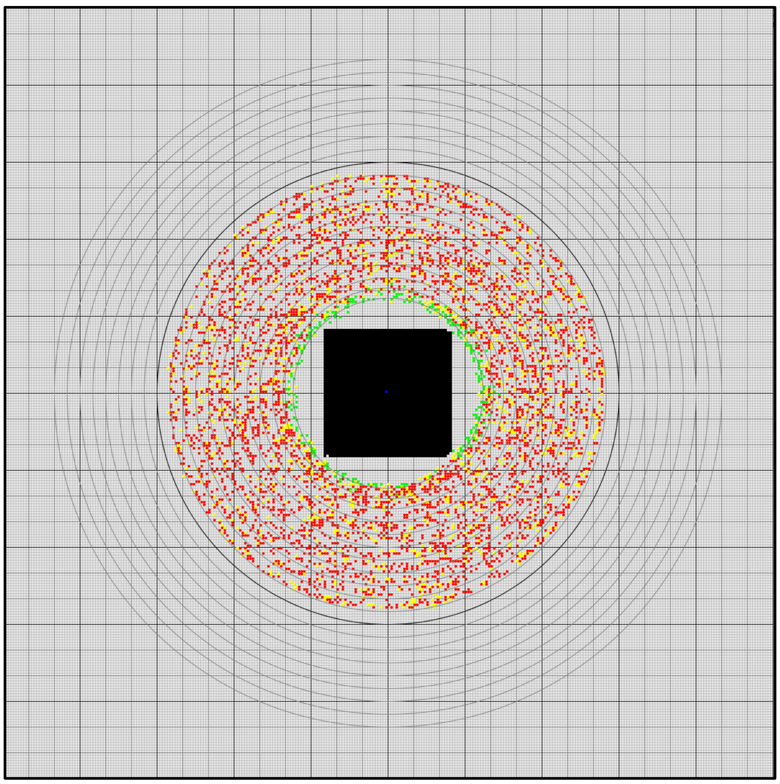


Figure 13: TawafSIM snapshot 2

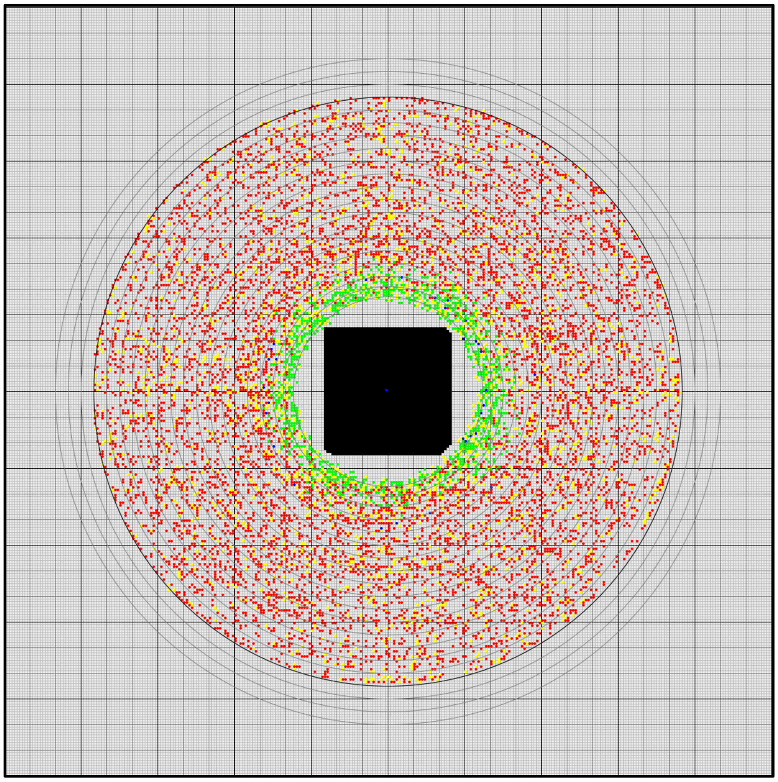


Figure 14: TawafSIM snapshot 3

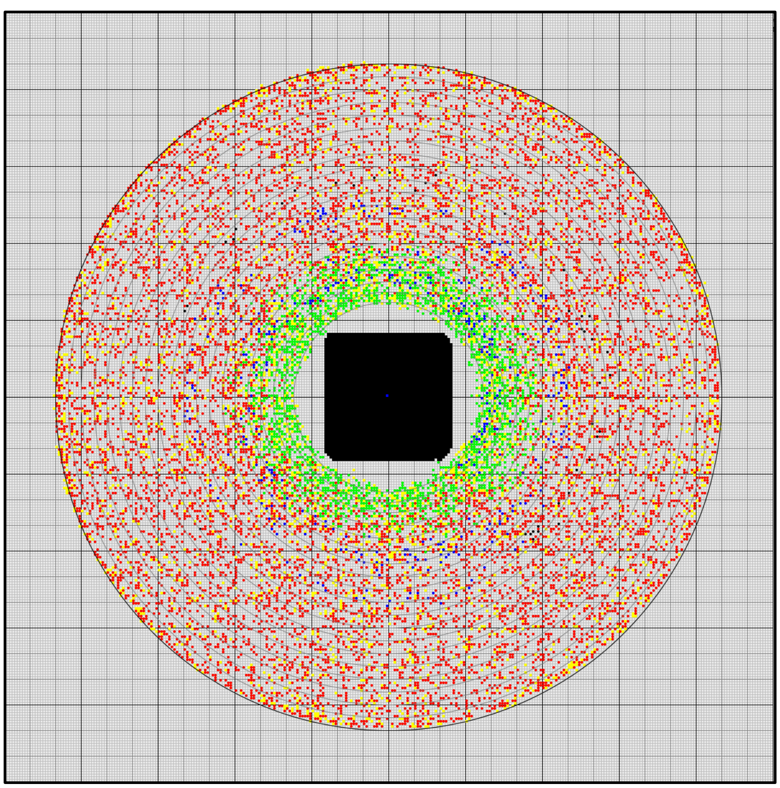


Figure 15: TawafSIM snapshot 4

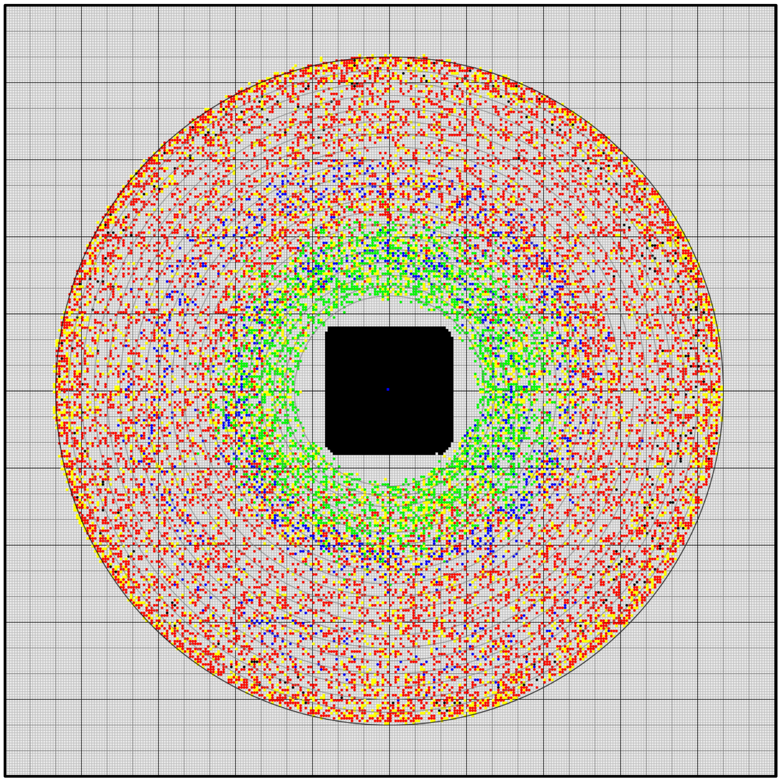


Figure 16: TawafSIM snapshot 5

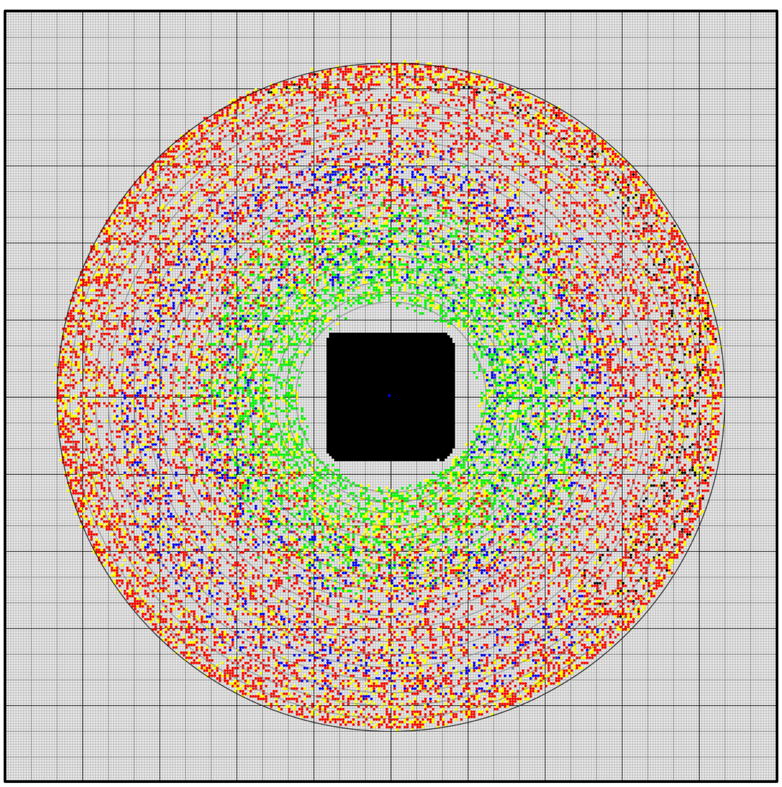
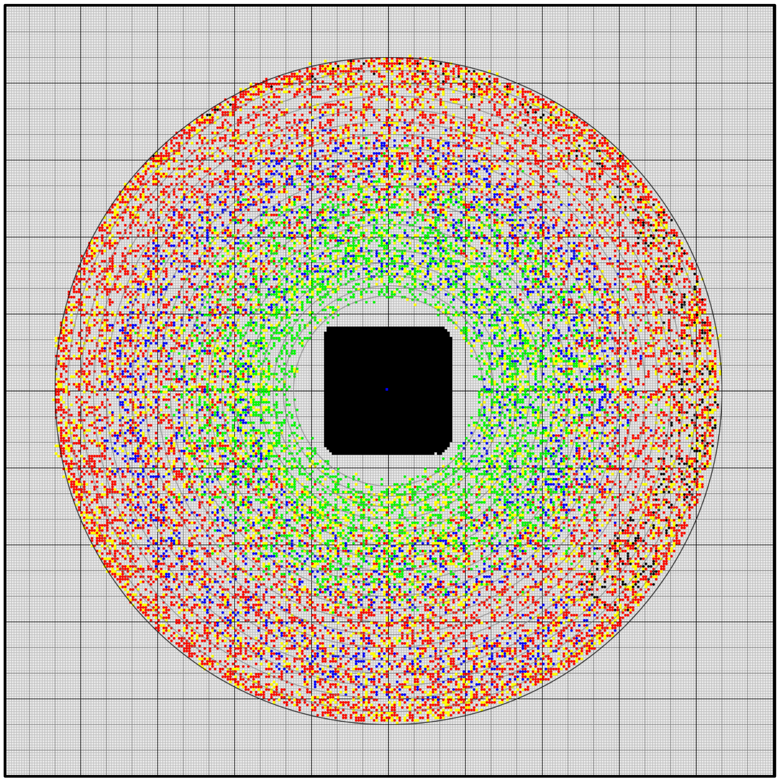


Figure 17: TawafSIM snapshot 6



4.3.1.1. Throughput (Average Time to Complete Rounds)

The shorter the Tawaf time, the greater the throughput. Figure 35 to Figure 44 in Appendix A show the average time to complete rounds 1 to 7 has a flat parabolic opening up shape for all the scenarios with the default scenario taking approximately 50 minutes to complete the Tawaf (i.e., all 7 rounds). As well, the following are noteworthy observations.

First, round 1 is always almost twice as long as the other rounds. The start of round one occurs once the pilgrim crosses the Tawaf start line for the first time. As such, depending on where a pilgrim enters the crowd boundary, a pilgrim may have to make up to one extra complete round before the start of round 1. Thus the time will be significantly more on average for round one. As well, the first round starts at the 130-foot crowd boundary since the metrics are recorded after the courtyard reaches its maximum pilgrim capacity; thus the first round has one of the longest distances to complete.

Second, rounds 2, 3, 4, and 5 generally get shorter because the pilgrims are spiralling inward or maintaining their radius, thus it takes less time to complete the shorter spirals whereas rounds 6 and 7 always increase because the pilgrims are spiralling out and the larger spiral distance takes longer to complete.

4.3.1.2. Satisfaction (Time Off the Desired Spiral Path)

The greater the percentage of time off the desired spiral path, the more distracted and dissatisfied the pilgrim is with trajectory changes during the Tawaf. Figure 45 to Figure 54 in Appendix B show the percentage of time off the desired spiral path for the pilgrim population generally has a skewed distribution to the high side of the mean, where the default scenario has approximately 45% of the pilgrims at the mean of 29% of the time off its desired spiral path.

4.3.1.3. Satisfaction (Number of Moore Neighbours)

The greater the number of Moore neighbours, the more congested and dissatisfied the pilgrim is in its immediate vicinity. Figure 55 to Figure 64 in Appendix C show the number of Moore neighbours for the pilgrim population generally has a skewed distribution to the high side of the mean, where the default scenario has the mean 2.39 Moore neighbours for approximately 25% of the time.

4.3.1.4. Satisfaction (Number of Gender Neighbours)

The greater the number of opposite gender Moore neighbours, the more uncomfortable and dissatisfied the pilgrim is in its immediate vicinity. Figure 65 to Figure 74 in Appendix D show the number of opposite gender Moore neighbours for the pilgrim population has a one-sided distribution, where the default scenario has approximately 40% of the pilgrims with the mean 0.90 opposite gender Moore neighbours.

4.3.1.5. Health (Exposure to Infecting Pilgrims)

The greater the exposure (accumulated time with infecting pilgrims divided by Tawaf time) to infecting Moore pilgrims, the greater the chance a susceptible pilgrim (who is non-infecting and non-immunized) will get infected. Figure 75 to Figure 84 in Appendix E show the percentage of maximum exposure to infecting pilgrims generally has a skewed distribution to the high side of the mean, where the default scenario has the mean 8.8% maximum exposure to infecting pilgrims for 64% of the susceptible pilgrims.

4.3.1.6. Safety (Low, Medium, and High Threat)

Each of the 42 scenarios generates three safety plots, which are incorporated into one figure each. Since the 42 figures convey similar information, only one safety figure is discussed, which is scenario 17 showing 40,000 maximum pilgrim capacity.

The first plot in Figure 90 (Appendix F) shows the percentage of courtyard grids that are in low (i.e., less than 2 pilgrims per Moore neighbourhood), medium (i.e., between 2 to 4 pilgrims per Moore neighbourhood), and high (i.e., greater than 4 pilgrims per Moore neighbourhood) threat levels during the simulation. It also shows during the first 2,286 second (38.1 minutes) the Tawaf courtyard starts to fill up with pilgrims; as this happens, the percentage of grids in low (medium) threat decrease (increases) to a steady state value. As well, at approximately 2,340 seconds, the number of grids in high level starts to materialize. Overall the plot shows at 40,000 maximum pilgrim capacity, approximately 50% of the grids are in low threat, 40% are in medium threat, and 10% are in high threat.

The second plot in Figure 90 shows the highest density values per grid experienced during the simulation. The crowd boundary has four distinct pilgrim density circular regions. The farthest outward crowd boundary has 1-2 pilgrims per Moore neighbourhood (i.e., 100-200 pilgrims/900ft^2) while the next crowd boundaries become increasingly denser at 2-3, 3-4, and 4-5 pilgrims per Moore neighbourhood while the rest of the courtyard has 3-4 pilgrims per Moore neighbourhood. Interestingly, the highest crowd density is 4-5 pilgrims per Moore neighbourhood, which occurs slightly inside the crowd boundary, which represents the area where the cross traffic effect is felt the most between pilgrims entering and exiting the Tawaf crowd. The center of the contour plot has 0-1, 1-2, and 2-3 pilgrims per Moore neighbourhood. The 0-1 circular region corresponds to the Kaaba building, where no pilgrims can make Tawaf whereas the 1-2 and 2-3 circular regions concentric to the Kaaba have less density than the rest of the courtyard at 3-4 because these grids are partially covered by the Kaaba minimum boundary where the Tawaf does not occur.

The third plot in Figure 90 shows the percent of time each grid is in high threat, which represents how long each grid remains in the high threat conditions. The plot clearly shows that the grids corresponding with the crowd boundary are in the high threat level the most (up to 60% of the time), with the highest percentage of time corresponding with the densest area in plot 2. In particular, the grids with the highest percentage of time are neither on the Tawaf line nor on the closest circular radius to the Kaaba, but at the cross traffic region.

4.3.2 Observations from Data Analysis of TawafSIM Generated Data

The impact of the twelve scenario categories on throughput, satisfaction, health, and safety are shown in Table 2 to Table 12 and discussed in detail in the following subsections. Note, each inner table entry includes top to bottom: metric value, change from default, and signed impact label. All the metric values are averages except for the safety metrics, which are maximum values. As well, change from the default values is the percentage of change except for the last two safety metrics, which are absolute change. Additionally, the scale for signed impact labels are: No Impact=[0,2); Low Impact=[2,10); Med Impact=[10,20); High impact=[20,30); and V. High=[30,∞). Second, each last row and column table entry includes: unsigned impact label and value. The scale for unsigned impact labels is: NO impact=[0,1], LOW impact=(1,2], MED impact=(2,3], HIGH impact=(3,4], and V. HIGH=(4,5]. Each last row entry is the average of unsigned column values. As well, each last column entry is the average of the unsigned throughput metric, average of satisfaction metrics, health metric, and average of safety metrics.

The observations from the data analysis of the TawafSIM generated data is grouped based on the scenario conducted.

4.3.2.1. Gender Scenarios

Pilgrim gender has no significant impact on Tawaf performance. The last row in Table 2 shows pilgrim strength has no significant impact on all the Tawaf metrics, except a low impact on satisfaction. Additionally, the last column in Table 2 shows the gender scenarios have no significant impact on overall Tawaf performance. As such, pilgrim gender is not a significant factor in determining Tawaf performance, but the following are noteworthy observations.

First, as expected, gender has an extreme favourable impact on *Number of Gender Neighbours* (i.e., Satisfaction). Table 2 shows the single gender scenarios (i.e., 2 & 5) have no opposite gender neighbours. As well, the dominant gender scenarios (i.e., 3 & 4) have a significantly lower number of opposite gender neighbours than the default scenario. As such, although gender has a very high impact on *Number of Gender Neighbours*, it has an overall low impact on satisfaction and no significant impact on the overall Tawaf performance.

Second, a single gender male or female population (i.e., scenarios 2 & 5) has the same Tawaf performance. Although the movement behaviour for men is expected to be slightly more aggressive than that for women, in the female single gender population, the women behave the same as men in the absence of the opposite gender. As such, men and women have the same movement behaviour when separated from the opposite gender while the women are slightly more conservative in a mixed gender population.

Table 2: Gender impact on Tawaf crowd performance.

SCENARIO	*THROUGHPUT* *[Pilgrims/hr]*	*[% Time Distracted]*	*SATISFACTION* *[# Neighbours]*	*[# Gender Neighbours]*	*HEALTH* *[% Time Exposed]*	*[Pilgrims /900 ft^2]*	*SAFETY* *[% Grids in High Threat]*	*[% Time in High Threat]*	*IMPACT ON TAWAF*
Scenario 2: 100% Male 0% Female	29,703 (-1.9%) No	27.90 (+1.1%) No	2.35 (+0.4%) No	0.00 (-100.0%) V. High+	8.80 (-0.6%) No	392 (+0.5%) No	0 (0%) No	0 (0%) No	**NO (0.42)**
Scenario 3: 75% Male 25% Female	30,843 (+1.9%) No	26.90 (-2.5%) Low+	2.34 (0.0%) No	0.64 (-29.9%) High+	8.65 (-2.3%) Low+	384 (-1.5%) No	0 (0%) No	0 (0%) No	**NO (1.00)**
Default: 60% Male 40% Female	30,283 n/a n/a	27.60 n/a n/a	2.34 n/a n/a	0.90 n/a n/a	8.85 n/a n/a	390 n/a n/a	0 n/a n/a	0 n/a n/a	**N/A**
Scenario 4: 25% Male 75% Female	30,540 (+0.8%) No	27.50 (-0.4%) No	2.29 (-2.1%) Low+	0.73 (-19.9%) Med+	8.65 (-2.3%) Low+	388 (-0.5%) No	0 (0%) No	0 (0%) No	**NO (0.92)**
Scenario 5: 0% Male 100% Female	29,703 (-1.9%) No	27.80 (+0.7%) No	2.35 (+0.4%) No	0.00 (-100.0%) V. High+	8.85 (0.0%) No	390 (0.0%) No	0 (0%) No	0 (0%) No	**NO (0.42)**
IMPACT ON METRIC		**NO (0.50)**	**NO (0.5)**	**V. HIGH (4.25)**		**NO (0.00)**	**NO (0.00)**	**NO (0.00)**	
	NO (0.00)		**LOW (1.75)**		**NO (1.00)**		**NO (0.00)**		**NO (0.69)**

Third, dominant male and female gender populations have a different satisfaction experience. Although both dominant gender populations have a slightly lower exposure to infected pilgrims, male dominant populations also are slightly less distracted while female dominant populations have slightly fewer Moore neighbours. It would seem the male movement behaviour to spiral inward more aggressively allows the male dominant population to make fewer trajectory changes while keeping a larger buffer with the opposite gender whereas the female movement behaviour to spiral inward less aggressively in the mixed gender population while maintaining a buffer with the opposite gender helps to keep all the pilgrims slightly more separated from each other.

4.3.2.2. Constant Rate of Pilgrim Entry Scenarios

Constant rate of pilgrim entry into the Tawaf courtyard has an overall low impact on Tawaf performance. The last row in Table 3 for scenarios 6 to 8 shows constant pilgrim rate of entry has a low impact on throughput, satisfaction, and health along with no significant impact on safety. Additionally, the last column in Table 3 for scenarios 6 to 8 shows that below the 20 pilgrims per second default scenario, the overall Tawaf impact is low with no significant impact otherwise. As such, constant rate of pilgrim entry into the courtyard has a low significance in determining Tawaf performance with the following noteworthy observations.

First, Table 3 shows when the pilgrim rate of entry increases from 10 to 25 pilgrims per second there is:

1. Low favourable increase in Throughput.
2. Medium unfavourable increase in Percent Time Distracted (i.e., Satisfaction).

Table 3: Rate of entry impact on Tawaf crowd performance.

SCENARIO	*THROUGHPUT* *[Pilgrims/hr]*	*SATISFACTION* *[% Time Distracted]*	*[# Neighbours]*	*[# Gender Neighbours]*	*HEALTH* *[% Time Exposed]*	*SAFETY* *[Pilgrims /900 ft²]*	*[% Grids in High Threat]*	*[% Time in High Threat]*	*IMPACT ON TAWAF*
Scenario 6: 10 Pilgrims/sec	28,902 (-4.6%) Low-	22.20 (-19.6%) Med+	2.25 (-3.8%) Low+	0.90 (1.000) No	7.45 (-15.8%) Med+	397 (+1.8%) No	0 (0%) No	0 (0%) No	**LOW (1.67)**
Scenario 7: 15 Pilgrims/sec	29,831 (-1.5%) No	25.60 (-7.2%) Low+	2.34 (0.0%) No	0.91 (+1.1%) No	8.35 (-5.6%) Low+	389 (-0.3%) No	0 (0%) No	0 (0%) No	**LOW (1.17)**
Default: 20 Pilgrims/sec	30,283 n/a n/a	27.60 n/a n/a	2.34 n/a n/a	0.90 n/a n/a	8.85 n/a n/a	390 n/a n/a	0 n/a n/a	0 n/a n/a	**N/A**
Scenario 8: 25 Pilgrims/sec	30,612 (+1.1%) No	29.00 (+5.1%) Low-	2.41 (+3.0%) Low-	0.89 (-1.1%) No	8.95 (+1.1%) No	380 (-2.6%) Low+	0 (0%) No	0 (0%) No	**NO (0.67)**
Scenario 9: 300 sec Burst	30,181 (-0.3%) No	25.40 (-8.0%) Low+	2.29 (-2.1%) Low+	0.91 (+1.1%) No	8.20 (-7.3%) Low+	384 (-1.5%) No	0 (0%) No	0 (0%) No	**NO (0.83)**
Scenario 10: 600 sec Burst	30,706 (+1.4%) No	25.00 (-9.4%) Low+	2.34 (0.0%) No	0.91 (+1.1%) No	8.25 (-6.8%) Low+	386 (-1.0%) No	0 (0%) No	0 (0%) No	**NO (0.67)**
Scenario 11: 900 sec Burst	30,633 (+1.2%) No	24.20 (-12.3%) Med+	2.37 (+1.3%) No	0.91 (+1.1%) No	8.05 (-9.0%) Low+	387 (-0.8%) No	0 (0%) No	0 (0%) No	**NO (0.75)**
IMPACT ON METRIC		**MED (2.33)** **MED (2.33)**	**LOW (1.33)** **NO (0.67)**	**NO (0.67)** **NO (0.00)**		**NO (0.67)** **NO (0.00)**	**NO (0.00)** **NO (0.00)**	**NO (0.00)** **NO (0.00)**	
[Scenarios 6-8] **[Scenarios 9-11]**	**LOW (1.33)** **NO (0.67)**		**LOW (1.44)** **NO (1.00)**		**LOW (1.67)** **LOW (2.00)**		**NO (0.22)** **NO (0.00)**		**LOW (1.17)** **NO (0.75)**

3. Low unfavourable increase in Number of Neighbours (i.e., Satisfaction).
4. Low unfavourable increase in Percent Time Exposed (i.e., Health).

It would seem, as the constant rate of entry increases from 10 to 25 pilgrims per second, the number of local neighbours around the cross-traffic Tawaf boundary slightly increases, and the pilgrims become much more distracted as they make more frequent trajectory changes, which leads to a faster rate of spiralling that decreases the average Tawaf time and increases the throughput. As well, the percent of time pilgrims are exposed to infected pilgrims increases as the rate of pilgrim entry increases because local congestion increases. Therefore, a low (high) pilgrim rate of entry has a positive (negative) impact on satisfaction and health but a negative (positive) impact on throughput.

Second, at the highest rate of entry, the macro-congestion level (i.e., *Pilgrims per 900 ft^2*) unexpectedly decreases. Although Table 3 shows scenarios 6 to 8 have no overall significant impact on *Pilgrims per 900 ft^2*, at 25 pilgrims per second, there is a decrease in *Pilgrims per 900 ft^2*, which is counter intuitive. It would seem, although the micro-level congestion level is high at the highest level of pilgrim rate of entry, the macro-level congestion slightly decreases due to the higher rate of spiralling, which disperses the pilgrims. This is clearly shown in Figure 86 (Appendix F), where the pilgrims do not disperse as quickly at 10 pilgrims per second rate, which results in a higher overall macro-congestion level. As such, when the pilgrim rate of entry increases, the pilgrims autonomously disperse quicker, which results in decreasing the macro-level congestion level despite an increase in micro-level congestion around the cross traffic Tawaf boundary.

Third, the increase in the rate of pilgrim entry does not impact the number of gender neighbours. As pilgrim rate of entry increases from 10 to 25 pilgrims per second, the number of Moore neighbours increases, but the number of gender neighbours remains the same. It would seem at the 25,000 maximum pilgrim capacity there are enough empty spaces for the opposite genders to use to maintain the same gender buffer.

4.3.2.3. Bursty Rate of Entry Scenarios

Bursty pilgrim rate of entry into the Tawaf courtyard has overall no significant impact on Tawaf performance. The last row in Table 3 for scenarios 9 to 11 shows bursty pilgrim rate of entry has a low impact on health with no significant impact on throughput, satisfaction, or safety. Additionally, the last column in Table 3 for scenarios 9 to 11 shows there is no significant impact by varying the burst length from 5 minutes to 15 minutes where each burst cycle is for 10, 20, or 30 pilgrims per second. As such, bursty pilgrim rate of entry into the courtyard has no significance in determining Tawaf performance but has the following noteworthy observations.

First, for bursty pilgrim rate of entry, there is always a favourable impact on both *Percent Time Distracted* (i.e., satisfaction) and health. Table 3 shows for bursty pilgrim rate of entry, there is:

1. Medium favourable decrease in Percent Time Distracted (i.e., Satisfaction).
2. Low favourable decrease in Percent Time Exposed (i.e., Health).

It would seem, a bursty pilgrim rate of entry compared to the default constant rate of entry results in favourable non-uniform crowd conditions, which leads to fewer trajectory changes, thus decreasing *Percent Time Distracted* (i.e., Satisfaction) and in turn decreasing *Percent Time Exposed* to infecting pilgrim neighbours. Therefore, bursty pilgrim rate of entry has a favourable impact on *Percent Time Distracted* (i.e., Satisfaction) and health, although it is unclear how the favourable non-uniform emergent behaviour materializes as discussed below.

Second, bursty pilgrim rate of entry into the courtyard leads to non-uniform crowd behaviour. Figure 36 shows the average time to complete rounds 1, 6, and 7 decreases as the burst duration increases, but not as clearly for rounds 2, 3, 4, and 5 because the former rounds represent pure spiral inward (outward) trajectories for round 1 (rounds 6 and 7) while each of the latter rounds have a combination of spiralling inwards and maintaining circle dynamics. As such, bursty traffic causes non-uniform crowd conditions.

Third, if the burst duration increases too much, it may decrease the spiralling inward rate. Figure 87 (Appendix F) shows with 900 second burst duration, there is a less dense inner crowd. It would seem that if the burst duration is long enough, it allows the low rate of entry portion of the burst cycle to impact the inner crowd density as was shown in Figure 86 (Appendix F). Therefore, a long burst duration may result in a less dense core and more density at the cross traffic crowd boundary.

4.3.2.4. Entry Access Scenarios

Courtyard circular entry access has an overall negligible impact on Tawaf performance. The last row in Table 4 shows entry access has low impact on throughput and satisfaction with negligible impact on health and safety. Additionally, the last column in Table 4 shows when the entry access is restricted to 25%, there is low impact on overall Tawaf performance; otherwise, there is no significant impact. Therefore, circular entry is not a critical factor in determining Tawaf performance; however, the following observations are noteworthy.

First, Table 4 shows when the entry access increases from 25% to 100%, there is:

1. Low favourable increase in Throughput.
2. Low favourable decrease in *Percent Time Distracted* (i.e., Satisfaction).

It would seem, as the circular entry is restricted from 100% to 25%, the same numbers of pilgrims not only enter the Tawaf crowd from a compressed area, which increases *Percent Time Distracted* (i.e., Satisfaction) but also have to travel longer as shown in Figure 37 to complete the first round since the start of the entry access always starts from the Tawaf line that leads to an increase in average Tawaf time, which decreases throughput. Therefore, circular entry access has a low impact on throughput and satisfaction.

Second, if enough empty spaces exist in the courtyard, the pilgrims self organize to maintain almost the same level of Tawaf performance. Table 4 shows while the circular entry is greater than the 25% tipping point, the pilgrims are able to disperse into the empty spaces by making more trajectory changes. Therefore, restricting the courtyard entry to 25% is a tipping point to change the Tawaf performance for *Number Neighbours* (i.e., satisfaction), health, and *Pilgrims per 900* ft^2 (i.e., safety).

Table 4: Courtyard access impact on Tawaf crowd performance.

SCENARIO	*THROUGHPUT*	*SATISFACTION*			*HEALTH*	*SAFETY*			*IMPACT ON TAWAF*
	[Pilgrims/hr]	*[% Time Distracted]*	*[# Neighbours]*	*[# Gender Neighbours]*	*[% Time Exposed]*	*[Pilgrims /900 ft^2]*	*[% Grids in High Threat]*	*[% Time in High Threat]*	
Scenario 12: 25% Access	28,986 (-4.3%) Low-	29.20 (+5.8%) Low-	2.39 (+2.1%) Low-	0.89 (-1.1%) No	9.05 (+2.3%) Low-	380 (-3.6%) Low+	0 (0%) No	0 (0%) No	**LOW (1.50)**
Scenario 13: 50% Access	29,259 (-3.4%) Low-	28.40 (+2.9%) Low-	2.34 (0.0%) No	0.90 (0.0%) No	8.85 (0.0%) No	390 (0.0%) No	0 (0%) No	0 (0%) No	**NO (0.67)**
Scenario 14: 75% Access	29,762 (-1.7%) No	28.00 (+1.4%) No	2.34 (0.0%) No	0.90 (0.0%) No	8.95 (0.0%) No	390 (0.0%) No	0 (0%) No	0 (0%) No	**NO (0.50)**
Default: 100% Access	30,283 n/a n/a	27.60 n/a n/a	2.34 n/a n/a	0.90 n/a n/a	8.85 n/a n/a	390 n/a n/a	0 n/a n/a	0 n/a n/a	**N/A**
IMPACT ON METRIC		**LOW (1.33)**	**NO (0.67)**	**NO (0.00)**		**NO (0.67)**	**NO (0.00)**	**NO (0.00)**	
	LOW (1.33)	**LOW (1.11)**			**NO (0.67)**	**NO (0.22)**			**NO (0.89)**

4.3.2.5. Maximum Pilgrim Capacity Scenarios

Maximum pilgrim capacity in the courtyard has a medium impact on Tawaf performance. The last row in Table 5 shows maximum pilgrim capacity has the potential to have a very high impact on throughput, medium impact on satisfaction, low impact on health, and medium impact on safety. Additionally, the last column in Table 5 shows increasing the maximum pilgrim capacity from 25,000 to 30,000 results in a low impact on Tawaf performance while beyond 30,000 there is a high impact. Therefore, maximum pilgrim capacity is a significant factor in determining Tawaf performance with the following noteworthy observations.

First, as the maximum pilgrim capacity increases, it has an unfavourable impact on all Tawaf performance metrics except throughput. Table 5 shows when the maximum pilgrim capacity increases from 25,000 to 40,000, there is:

1. Very high favourable increase in Throughput.
2. Medium unfavourable increase in *Percent Time Distracted* (i.e., Satisfaction).
3. Medium unfavourable increase in *Number Neighbours* (i.e., Satisfaction).
4. Medium unfavourable increase *in Number Gender Neighbours* (i.e., Satisfaction).
5. Low unfavourable increase in *Percent Time Exposed* (i.e., Health).
6. Medium unfavourable increase in *Pilgrims per 900* ft^2 (i.e., Safety).
7. Medium unfavourable increase in *Percent Grids in High Threat* (i.e., Safety).
8. High unfavourable increase in *Percent Time in High Threat* (i.e., Safety).

It would seem from Figure 38 (Appendix A) as expected, with an increase in maximum pilgrim capacity, the average time to complete each of the seven rounds increases. This

Table 5: Capacity impact on Tawaf crowd performance.

SCENARIO	*THROUGHPUT* *[Pilgrims/hr]*	*SATISFACTION* *[% Time Distracted]*	*[# Neighbours]*	*[# Gender Neighbours]*	*HEALTH* *[% Time Exposed]*	*SAFETY* *[Pilgrims /900 ft^2]*	*[% Grids in High Threat]*	*[% Time in High Threat]*	*IMPACT ON TAWAF*
Default: 25,000 pilgrims	30,283 n/a n/a	27.60 n/a n/a	2.34 n/a n/a	0.90 n/a n/a	8.85 n/a n/a	390 n/a n/a	0 n/a n/a	0 n/a n/a	**N/A**
Scenario 15: 30,000 pilgrims	35,031 (+15.7%) Med+	29.10 (+8.5%) Low-	2.54 (8.5%) Low-	0.93 (+3.3%) Low-	8.95 (+1.1%) No	411 (+5.4%) Low-	3 (+3%) Low-	6 (+6%) Low-	**LOW (1.75)**
Scenario 16: 35,000 pilgrims	39,461 (+30.3%) V. High+	29.30 (+6.2%) Low-	2.64 (12.8%) Med-	0.99 (+10.0%) Med-	9.25 (+4.5%) Low-	445 (+14.1%) Med-	6 (+6%) Low-	47 (+47%) V. High-	**HIGH (3.25)**
Scenario 17: 40,000 pilgrims	44,417 (46.7%) V. High+	31.30 (13.4%) Med-	2.81 (20.1%) High-	1.05 (+16.7%) Med-	9.50 (+7.3%) Low-	466 (+19.5%) Med-	11 (+11%) Med-	55 (+55%) V. High-	**HIGH (3.50)**
IMPACT ON METRIC		**MED (2.33)**	**MED (3.00)**	**MED (2.67)**		**MED (2.67)**	**MED (2.33)**	**HIGH (4.00)**	
	V. HIGH (4.33)	**MED (2.67)**			**LOW (1.33)**	**MED (3.00)**			**MED (2.83)**

is because, with an increase in maximum pilgrim capacity, the increase in crowd density prevents the pilgrims from moving to their preferred macro-level spiral-based next position as it is more likely to be occupied; therefore, the pilgrim chooses an alternative position in its Moore neighbourhood which is probably not the optimum position with respect to its spiralling direction. This increase in average Tawaf time and maximum number of pilgrims negatively impacts the other metrics. As a result, with an increase in maximum pilgrim capacity in the courtyard, only throughput is favourably impacted.

Second, even at high maximum pilgrim capacity, the percent of grids in high threat is not widespread. At 40,000 maximum pilgrim capacity, which represents 82% of the total simulated Tawaf courtyard space, there are at most 11% of the courtyard grids in high threat, which are at the inner edge of the Tawaf crowd boundary where cross traffic is the highest. This ability to maintain a uniform macro congestion level is due to removing the mob at the Black Stone and Kaaba walls. Therefore, high threat levels can be managed to acceptable levels by providing an unobstructed circular path and limiting maximum pilgrim capacity to 82% of the total courtyard capacity.

Third, a higher density crowd does not significantly impact the health metric (i.e., percent of time exposed to infecting neighbours). A 60% increase in the maximum pilgrim capacity only increases percent time exposed to infecting pilgrims by 7%. Therefore, extreme crowded conditions alone do not significantly increase the exposure to infecting individuals.

Fourth, a safety tipping point occurs when maximum pilgrim capacity reaches 71% of the total Tawaf area. Table 5 shows at 30,000 maximum pilgrim capacity, the percent of grids in high threat is at most 6% of the time while at 35,000, the time in high threat is

47%. As well, Figure 88, Figure 89, and Figure 90 (Appendix F) compared to Figure 85 (Appendix F) shows the cross-traffic area becoming more prominent. Therefore, the cross traffic crowd boundary becomes significantly more dangerous suddenly at 71% of the total courtyard pilgrim capacity (i.e., 35,000 maximum pilgrim capacity).

Fifth, at a critical maximum pilgrim capacity, the pilgrims display orthogonal movement. With an increase in maximum pilgrim capacity in the courtyard, the pilgrims average time to complete a round increases except in rounds 6 and 7, when the maximum pilgrim capacity reaches a critical point (35,000 maximum pilgrims, which is 72% of the maximum Tawaf crowd area), the average time to complete a round decreases. This unexpected emergent behaviour shows that when the maximum crowd is above a critical level, the increase in crowd density and congestion leads the pilgrim to make more frequent changes to its preferred macro spiral-based next position which are more likely in the direction of the crowd boundary, thus leading to a more orthogonal line of path to exit the crowd boundary, which is a shorter path out of the crowd. Therefore, emergent orthogonal movement is displayed when maximum pilgrim capacity reaches a critical level.

4.3.2.6. Pilgrim Manner Scenarios

Pilgrim manner has no significant impact on Tawaf performance. The last row in Table 6 shows pilgrim manners have no significant impact on all the Tawaf metrics. Additionally, the last column in Table 6 shows 100% low, medium, or high manner pilgrim populations have no significant impact on overall Tawaf performance. Therefore, pilgrim manners are not a significant factor in determining Tawaf performance; however, the following are noteworthy observations.

Table 6: Manner impact on Tawaf crowd performance.

SCENARIO	THROUGHPUT [Pilgrims/hr]	SATISFACTION [% Time Distracted]	SATISFACTION [# Neighbours]	SATISFACTION [# Gender Neighbours]	HEALTH [% Time Exposed]	SAFETY [Pilgrims /900 ft^2]	SAFETY [% Grids in High Threat]	SAFETY [% Time in High Threat]	IMPACT ON TAWAF
Default	30,283 n/a n/a	27.60 n/a n/a	2.34 n/a n/a	0.90 n/a n/a	8.85 n/a n/a	390 n/a n/a	0 n/a n/a	0 n/a n/a	**N/A**
Scenario 18: 100% Low	30,696 (+1.4%) No	27.30 (-1.1%) No	2.34 (0.0%) No	0.83 (-7.8%) Low+	8.70 (-1.7%) No	384 (-1.5%) No	0 (0%) No	0 (0%) No	**NO (0.17)**
Scenario 19: 100% Medium	28,187 (+0.9%) No	27.60 (0.0%) No	2.34 (0.0%) No	0.83 (-7.8%) Low+	8.65 (-2.3%) Low+	390 (0.0%) No	0 (0%) No	0 (0%) No	**NO (0.67)**
Scenario 20: 100% High	27,761 (-3.1%) Low-	28.90 (+4.7%) Low-	2.52 (+7.7%) Low-	0.90 (0.0%) No	9.00 (+1.7%) No	397 (+1.8%) No	0 (0%) No	0 (0%) No	**NO (0.83)**
IMPACT ON METRIC		**NO (0.67)**	**NO (0.67)**	**LOW (1.33)**		**NO (0.00)**	**NO (0.00)**	**NO (0.00)**	
	NO (0.67)	**NO (0.89)**			**NO (0.67)**	**NO (0.00)**			**NO (0.56)**

First, the typical negative impact to satisfaction, health, and safety from low mannered pilgrim populations (i.e., 100% low or 100% medium) is unexpectedly avoided when the Tawaf area is 50% empty (i.e., at 25,000 maximum pilgrims). It would seem when there are sufficient empty spaces in the Tawaf courtyard, the low manner pilgrim micro-level movement settings allow them to spiral more rapidly but does not create any adverse effects on any of the Tawaf metrics. In fact, *Number of Gender Neighbours* (i.e., Satisfaction) actually improved. Therefore, when the Tawaf courtyard is maintained at 50% maximum capacity, low manner pilgrim populations do not produce negative impacts on Tawaf performance.

Second, the 100% high manner pilgrim scenario did not have a favourable impact as expected on *Number of Neighbours* or *Number of Gender Neighbours*. As expected, the high manner pilgrims micro-level movement algorithm made them more sensitive to their surroundings, which lead to a longer average Tawaf time due to the additional trajectory changes. However, these additional manner inspired trajectory changes increased the average number of neighbours while maintaining the average number of gender neighbours. Therefore, higher manner individuals do not necessarily get the higher level of satisfaction from being more considerate in their micro-movement decisions.

4.3.2.7. Pilgrim Speed Scenarios

Pilgrim speed has a high impact on Tawaf performance. The last row in Table 7 shows pilgrim speed has very high impact on throughput along with medium impact on satisfaction, health, and safety. Additionally, the last column in Table 7 shows 100% low and high speed pilgrim populations have a high impact on Tawaf performance while 100%

Table 7: Speed impact on Tawaf crowd performance.

SCENARIO	*THROUGHPUT*	*SATISFACTION*			*HEALTH*	*SAFETY*			*IMPACT ON TAWAF*
	[Pilgrims/hr]	*[% Time Distracted]*	*[# Neighbours]*	*[# Gender Neighbours]*	*[% Time Exposed]*	*[Pilgrims /900 ft^2]*	*[% Grids in High Threat]*	*[% Time in High Threat]*	
Default	30,283 n/a n/a	27.60 n/a n/a	2.34 n/a n/a	0.90 n/a n/a	8.85 n/a n/a	390 n/a n/a	0 n/a n/a	0 n/a n/a	**N/A**
Scenario 21: 100% Low	20,994 (-31.7%) V. High-	29.00 (+5.1%) Low-	2.74 (+17.1%) Med-	0.98 (+8.9%) Low-	11.85 (+33.9%) V. High-	489 (+25.4%) High-	16 (+16%) Med-	23 (+23%) High-	**HIGH (4.00)**
Scenario 22: 100% Medium	35,857 (+18.4%) Med+	20.20 (-26.8%) High+	2.50 (+6.8%) Low-	0.88 (-2.2%) Low+	8.75 (-1.1%) No	450 (+15.4%) Med-	14 (+14%) Med-	56 (+56%) V. High-	**MED (2.33)**
Scenario 23: 100% High	49,234 (+62.6%) V. High+	18.10 (-34.4%) V. High+	2.31 (-1.3%) No	0.85 (-5.6%) Low+	7.65 (-13.6%) Med+	444 (+13.8%) Med-	3 (+3%) Low-	19 (+19%) Med-	**HIGH (3.25)**
IMPACT ON METRIC		**HIGH (3.67)**	**LOW (1.67)**	**LOW (2.00)**		**HIGH (3.33)**	**MED (2.67)**	**HIGH (4.00)**	
	V. HIGH (4.33)	**MED (2.44)**			**MED (2.67)**	**MED (3.33)**			**HIGH (3.19)**

medium speed pilgrim population has medium impact. Therefore, pilgrim speed is an extremely significant factor in determining Tawaf performance with the following noteworthy observations.

First, in general, as the pilgrim population speed distribution increases, it has a favourable impact on all Tawaf performance metrics except safety. Table 7 shows compared to the default (i.e., 25% low, 50% medium, 25% high) pilgrim population speed distribution, when the speed distribution increases from 100% low to 100% medium to 100% high, there is:

1. Extreme favourable increase in Throughput.
2. High favourable decrease in *Percent Time Distracted* (i.e., Satisfaction).
3. Low favourable decrease in *Number of Neighbours* (i.e., Satisfaction).
4. Low favourable decrease in *Number of Gender Neighbours* (i.e., Satisfaction).
5. Medium favourable decrease in *Percent Time Exposed* (i.e., Health).

It would seem, as expected, the shorter Tawaf time due to a faster speed has a favourable impact on throughput, percent time distracted, and percent time exposed to infecting pilgrims. As well, the faster speed also seems to allow the pilgrims to make active decisions to navigate between the other pilgrims thus slightly decreasing the number of neighbours and number of gender neighbours. Therefore, a high speed pilgrim distribution has a high positive impact on Tawaf performance except for safety while a low speed distribution has a high negative impact.

Second, a non-homogenous pilgrim population speed distribution (e.g., 25% low, 50% medium, 25% high) has a favourable impact on safety whereas a homogeneous speed distribution has an unfavourable impact. The safety metrics in Table 7 show that compared to the default non-homogenous speed scenario, the homogenous low, medium, and high speed scenarios have a medium unfavourable impact on safety. Therefore, a pilgrim population with normal speed distribution provides better safety.

Third, even at a 50% maximum Tawaf courtyard pilgrim capacity (i.e., 25,000 maximum pilgrims), pilgrims cannot maintain their maximum free flow speed throughout the Tawaf. A three time increase in speed for low (i.e., 1 foot per second) to high (3 feet per second) speed pilgrims results in only a 0.42 times decrease in Tawaf time instead of the ideal 0.33 times decrease in Tawaf time. Therefore, pilgrims always have an average speed lower than their maximum free flow speed.

Fourth, as homogeneous pilgrim speed decreases, it has a significant negative impact on macro-level congestion and percent of time in high threat. Figure 91, Figure 92, and Figure 93 (Appendix F) show as homogeneous speed decreases, the highest grid density and percent time in high threat quickly spreads throughout the inner courtyard. Therefore, low speed has a dramatic unfavourable impact on safety.

4.3.2.8. Pilgrim Strength Scenarios

Pilgrim strength has no significant impact on Tawaf performance. The last row in Table 8 shows pilgrim strength has no significant impact on all the Tawaf metrics. Additionally, the last column in Table 8 shows 100% low, medium, or high speed pilgrim populations have no significant impact on overall Tawaf performance. As such, pilgrim strength is not significant factor in determining Tawaf performance, but the following is a noteworthy observation.

Table 8: Strength impact on Tawaf crowd performance.

SCENARIO	THROUGHPUT [Pilgrims/hr]	SATISFACTION [% Time Distracted]	[# Neighbours]	[# Gender Neighbours]	HEALTH [% Time Exposed]	SAFETY [Pilgrims /900 ft^2]	[% Grids in High Threat]	[% Time in High Threat]	IMPACT ON TAWAF
Default	30,283 n/a n/a	27.60 n/a n/a	2.34 n/a n/a	0.90 n/a n/a	8.85 n/a n/a	390 n/a n/a	0 n/a n/a	0 n/a n/a	**N/A**
Scenario 24: 100% Low	30,560 (+0.9%) No	27.30 (-1.1%) No	2.34 (0.0%) No	0.83 (-7.8%) Low+	8.75 (-1.1%) No	387 (-0.8%) No	0 (0%) No	0 (0%) No	**NO (0.17)**
Scenario 25: 100% Medium	30,467 (+0.6%) No	27.10 (-1.1%) No	2.34 (0.0%) No	0.83 (-7.8%) Low+	8.75 (-1.1%) No	389 (-0.3%) No	0 (0%) No	0 (0%) No	**NO (0.17)**
Scenario 26: 100% High	30,644 (+1.2%) No	27.60 (0.0%) No	2.34 (0.0%) No	0.83 (-7.8%) Low+	8.75 (-1.1%) No	395 (+1.3%) No	0 (0%) No	0 (0%) No	**NO (0.17)**
IMPACT ON METRIC		**NO (0.00)**	**NO (0.00)**	**LOW (2.00)**		**NO (0.00)**	**NO (0.00)**	**NO (0.00)**	
	NO (0.00)	**NO (0.67)**			**NO (0.00)**	**NO (0.00)**			**NO (0.17)**

A pilgrim population at any homogenous strength level has a low favourable impact on *Number of Gender Neighbours* (i.e., Satisfaction). Table 8 shows for 100% low, medium, or high manner scenarios, the *Number of Gender Neighbours* are 8% lower than at the default non-homogenous distribution. It would seem the effect of low, medium, or high strength on the micro-level movement algorithm has less impact than having all the pilgrims behaving the same way, which might explain the similar values for each of the above metrics despite the strength level. Therefore, strength has no significant impact on overall satisfaction or overall Tawaf performance.

4.3.2.9. Pilgrim Desire to Touch Kaaba Scenarios

Pilgrim desire to touch the Kaaba has no significant impact on Tawaf performance. The last row in Table 9 shows the desire to touch the Kaaba has a low impact on satisfaction but no significant impact on throughput, health, or safety. Additionally, the last column in Table 9 shows 100% low, medium, or high pilgrim desire to touch the Kaaba have no significant impact on overall Tawaf performance. Therefore, pilgrim desire to touch the Kaaba is not a significant factor in determining Tawaf performance; however, the following is a noteworthy observation.

For a pilgrim population with homogenous (i.e., 100% low, 100% medium, or 100% high) desire to touch the Kaaba compared to the default (25% low, 50% medium, and 25% high), there is almost always:

1. Low unfavourable increase in *Percent Time Distracted* (i.e., Satisfaction).
2. Low unfavourable increase in *Number Neighbours* (i.e., Satisfaction).
3. Low favourable decrease in *Number Gender Neighbours* (i.e., Satisfaction).

Table 9: Desire to touch Kaaba impact on Tawaf crowd performance.

SCENARIO	*THROUGHPUT*	*SATISFACTION*			*HEALTH*	*SAFETY*			*IMPACT ON TAWAF*
	[Pilgrims/hr]	*[% Time Distracted]*	*[# Neighbours]*	*[# Gender Neighbours]*	*[% Time Exposed]*	*[Pilgrims /900 ft^2]*	*[% Grids in High Threat]*	*[% Time in High Threat]*	
Default	30,283 n/a n/a	27.60 n/a n/a	2.34 n/a n/a	0.90 n/a n/a	8.85 n/a n/a	390 n/a n/a	0 n/a n/a	0 n/a n/a	**N/A**
Scenario 27: 100% Low	29,831 (-1.5%) No	27.90 (+1.1%) No	2.41 (+3.0%) Low-	0.86 (-4.4%) Low+	8.90 (+0.6%) No	402 (+3.1%) Low-	1 (+1%) No	1 (+1%) No	**NO (0.50)**
Scenario 28: 100% Medium	29,811 (-1.6%) No	28.50 (+3.3%) Low-	2.41 (+3.0%) Low-	0.86 (-4.4%) Low+	8.75 (-1.1%) No	395 (+1.3%) No	0 (0%) No	0 (0%) No	**NO (0.67)**
Scenario 29: 100% High	29,693 (-1.9%) No	28.30 (+2.5%) Low-	2.41 (+3.0%) Low-	0.86 (-4.4%) Low+	8.80 (-0.6%) No	403 (+3.3%) Low-	1 (+1%) No	1 (+1%) No	**NO (0.67)**
IMPACT ON METRIC		**LOW (1.33)**	**LOW (2.00)**	**LOW (2.00)**		**LOW (1.33)**	**NO (0.00)**	**NO (0.00)**	
	NO (0.00)	**LOW (1.78)**			**NO (0.00)**	**NO (0.44)**			**NO (0.56)**

4. Low unfavourable increase in *Pilgrims per 900 ft*^{2} (i.e., Safety).

It would seem the effect of low, medium, or high desire to touch the Kaaba on the micro-level movement algorithm has less impact than having all the pilgrims behaving the same way, which might explain the similar values for each of the above metrics despite the desire level. Therefore, a pilgrim population with homogeneous desire to touch the Kaaba produces low unfavourable impact on overall satisfaction and *Pilgrims per 900 ft*^{2} (i.e., safety) but no significant impact on overall Tawaf performance.

4.3.2.10. Pilgrim Infecting Level Scenarios

Pilgrim infecting level has a very high impact on health, which leads to a low impact on overall Tawaf performance. The last row in Table 10 shows pilgrim-infecting level has a very high impact on health but no significant impact on other Tawaf metrics. Additionally, the last column in Table 10 shows pilgrim-infecting levels have either low or no significant impact on overall Tawaf performance. Therefore, pilgrim-infecting level is an extremely significant factor in determining health but not for any other Tawaf performance metrics; however, the following is a noteworthy observation.

Infecting level has a very high impact on health. Table 10 shows as infecting level increases from 10% to 50%, the percent time exposed to infecting pilgrims increases from 5% to 13%, which is almost a linear relationship. Therefore, infecting level has a very high impact on health.

Table 10: Infecting levels impact on Tawaf crowd performance.

SCENARIO	*THROUGHPUT* [Pilgrims/hr]	*SATISFACTION* [% Time Distracted]	[# Neighbours]	[# Gender Neighbours]	*HEALTH* [% Time Exposed]	*SAFETY* [Pilgrims /900 ft^2]	[% Grids in High Threat]	[% Time in High Threat]	*IMPACT ON TAWAF*
Scenario 30: 10% Infecting 20% Immunized	30,151 (-0.4%) No	27.60 (0.0%) No	2.34 (0.0%) No	0.90 (0.0%) No	4.95 (-44.1%) V. High+	397 (+1.8%) No	0 (0%) No	0 (0%) No	**LOW (1.25)**
Scenario 31: 20% Infecting 20% Immunized	30,334 (+0.2%) No	27.80 (+0.7%) No	2.34 (0.0%) No	0.90 (0.0%) No	6.90 (-22.0%) High+	387 (-0.8%) No	0 (0%) No	0 (0%) No	**NO (1.00)**
Default: 30% Infecting 20% Immunized	30,283 n/a n/a	27.60 n/a n/a	2.34 n/a n/a	0.90 n/a n/a	8.85 n/a n/a	390 n/a n/a	0 n/a n/a	0 n/a n/a	**N/A**
Scenario 32: 40% Infecting 20% Immunized	30,232 (-0.2%) No	27.60 (0.0%) No	2.34 (0.0%) No	0.90 (0.0%) No	11.15 (+26.0%) High-	397 (+1.8%) No	0 (0%) No	0 (0%) No	**NO (1.00)**
Scenario 33: 50% Infecting 20% Immunized	30,416 (+0.4%) No	27.80 (0.0%) No	2.34 (0.0%) No	0.90 (0.0%) No	13.00 (+46.9%) V. High-	391 (+0.2%) No	0 (0%) No	0 (0%) No	**LOW (1.25)**
IMPACT ON METRIC		**NO (0.00)**	**NO (0.00)**	**NO (0.00)**		**NO (0.00)**	**NO (0.00)**	**NO (0.00)**	
	NO (0.00)		**NO (0.00)**		**V. HIGH (4.50)**		**NO (0.00)**		**LOW (1.13)**

4.3.2.11. Pilgrim Immunization Scenarios

For a given percentage of infecting pilgrims performing Tawaf, increasing the pilgrim immunization level of the remaining pilgrims has no impact on Tawaf performance. The last row in Table 11 shows pilgrim immunization level has no impact on any of the metrics. Additionally, the last column in Table 11 shows varying the immunization level has no impact on overall Tawaf performance. Therefore, for a given percentage of infecting pilgrims performing Tawaf, increasing pilgrim immunization level does not impact Tawaf performance; however, the following is a noteworthy observation.

For a given percentage of infecting pilgrims performing Tawaf, increasing immunization level does not impact health exposure. Table 11 shows no significant health impact on the susceptible pilgrims when varying the immunization level from 0% to 50% when the pilgrim population has 30% infecting pilgrims (similar results were obtained for additional scenarios where infecting pilgrims were modified from 5% to 80%). It would seems the percentage of infecting pilgrims has an impact on health, but increasing the number of immunized pilgrims from the susceptible pilgrim population does not help create a barrier between the infecting and susceptible pilgrims. Therefore, for a given percentage of infecting pilgrims performing Tawaf, increasing immunization does not decrease the exposure to infecting pilgrims.

4.3.2.12. Pilgrim Degree Spiral-In Scenarios

Pilgrim degree of spiral inward has the highest impact on Tawaf performance. The last row in Table 12 shows degree of spiral-inward has high impact on throughput and

Table 11: Herd immunization levels impact on Tawaf crowd performance.

SCENARIO	*THROUGHPUT* *[Pilgrims/hr]*	*SATISFACTION* *[% Time Distracted]*	*[# Neighbours]*	*[# Gender Neighbours]*	*HEALTH* *[% Time Exposed]*	*SAFETY* *[Pilgrims /900 ft²]*	*[% Grids in High Threat]*	*[% Time in High Threat]*	*IMPACT ON TAWAF*
Scenario 34: 0% Immunized 30% Infecting	30,303 (+0.1%) No	27.80 (+0.7%) No	2.34 (0.0%) No	0.90 (0.0%) No	8.70 (-1.7%) No	388 (-0.5%) No	0 (0%) No	0 (0%) No	**NO (0.00)**
Scenario 35: 10% Immunized 30% Infecting	30,416 (+0.4%) No	27.50 (-0.4%) No	2.34 (0.0%) No	0.90 (0.0%) No	8.85 (0.0%) No	388 (-0.5%) No	0 (0%) No	0 (0%) No	**NO (0.00)**
Default: 20% Immunized 30% Infecting	30,283 n/a n/a	27.60 n/a n/a	2.34 n/a n/a	0.90 n/a n/a	8.85 n/a n/a	390 n/a n/a	0 n/a n/a	0 n/a n/a	**N/A**
Scenario 36: 30% Immunized 30% Infecting	30,334 (+0.2%) No	27.80 (+0.7%) No	2.34 (0.0%) No	0.90 (0.0%) No	8.70 (-1.7%) No	392 (+0.5%) No	0 (0%) No	0 (0%) No	**NO (0.00)**
Scenario 37: 40% Immunized 30% Infecting	30,232 (-0.2%) No	27.60 (0.0%) No	2.34 (0.0%) No	0.90 (0.0%) No	8.70 (-1.7%) No	393 (+0.7%) No	0 (0%) No	0 (0%) No	**NO (0.00)**
Scenario 38: 50% Immunized 30% Infecting	30,375 (+0.3%) No	27.50 (-0.4%) No	2.34 (0.0%) No	0.90 (0.0%) No	8.80 (-0.6%) No	391 (+0.3%) No	0 (0%) No	0 (0%) No	**NO (0.00)**
IMPACT ON METRIC		**NO (0.00)**	**NO (0.00)**	**NO (0.00)**		**NO (0.00)**	**NO (0.00)**	**NO (0.00)**	
	NO (0.00)	**NO (0.00)**			**NO (0.00)**	**NO (0.00)**			**NO (0.00)**

satisfaction with medium impact on health and safety. Additionally, the last column in Table 12 shows if 100% of the pilgrims spiral farthest inward on round 1 and 3, the impact on overall Tawaf performance is high; otherwise, if they spiral farthest inward on round 2 and 4, the impact is medium. Therefore, pilgrim degree of spiral inward is a significant factor in determining Tawaf performance with the following noteworthy observations.

First, the pilgrim degree of spiral inward has both favourable and unfavourable effect on throughput. Table 12 shows, compared to the default spiral farthest inward distribution (i.e., 25% in each of the four rounds), if all the pilgrims spiral farthest inward in round 1 or 2, the throughput increases very high (i.e., 36%) or low (i.e., 6%) respectively; otherwise, if the farthest inward occurs in round 3 or 4, there is a medium decrease in throughput of 13% and 17% respectively. Therefore, as expected, spiralling farthest inward sooner has a favourable impact on average Tawaf time and throughput while delaying it has an unfavourable impact.

Second, for a pilgrim population with homogenous (i.e., 100% round 1, 100% round 2, 100% round 3, or 100% round 4) pilgrim degree spiral-inward compared to the uniform default scenario, there is:

1. High unfavourable increase in *Percent Time Distracted* (i.e., Satisfaction).
2. High unfavourable increase in *Number Neighbours* (i.e., Satisfaction).
3. Very high unfavourable increase in *Number Gender Neighbours* (i.e., Satisfaction).
4. Medium unfavourable increase in *Pilgrims per 900* ft^2 (i.e., Safety).
5. Low unfavourable increase in *Percent Grids in High Threat* (i.e., Safety).

Table 12: Degree spiralling impact on Tawaf crowd performance.

SCENARIO	*THROUGHPUT* *[Pilgrims/hr]*	*SATISFACTION* *[% Time Distracted]*	*[# Neighbours]*	*[# Gender Neighbours]*	*HEALTH* *[% Time Exposed]*	*SAFETY* *[Pilgrims /900 ft^2]*	*[% Grids in High Threat]*	*[% Time in High Threat]*	*IMPACT ON TAWAF*
Default:	30,283 n/a n/a	27.60 n/a n/a	2.34 n/a n/a	0.90 n/a n/a	8.85 n/a n/a	390 n/a n/a	0 n/a n/a	0 n/a n/a	**N/A**
Scenario 39: 100% Round 1	41,077 (+35.6%) V. High+	31.10 (+12.7%) Med-	3.10 (+32.5%) V. High-	1.46 (+62.2%) V. High-	9.25 (+4.5%) Low-	518 (+32.8%) V. High-	8 (+8%) Low-	88 (+88%) V. High-	**HIGH (3.83)**
Scenario 40: 100% Round 2	31,960 (+5.5%) Low+	32.30 (+17.0%) Med-	2.84 (+21.4%) High-	1.38 (+53.3%) V. High-	9.80 (+10.7%) Med-	449 (+15.1%) Med-	7 (+7%) Low-	26 (+26%) High-	**MED (3.00)**
Scenario 41: 100% Round 3	26,463 (-12.6%) Med-	34.70 (+25.7%) High-	2.74 (+17.1%) Med-	1.25 (+38.9%) V. High-	10.45 (+18.1%) Med-	428 (+9.7%) Low-	4 (+4%) Low-	12 (+12%) Med-	**HIGH (3.08)**
Scenario 42: 100% Round 4	25,084 (-17.2%) Med-	41.30 (+49.6%) V. High-	2.72 (+16.2%) Med-	1.30 (+44.4%) V. High-	11.50 (+29.9%) High-	404 (+3.6%) Low-	1 (+1%) No	1 (+1%) No	**MED (3.00)**
IMPACT ON METRIC		**HIGH (3.75)**	**HIGH (3.75)**	**V. HIGH (5.00)**		**MED (3.00)**	**LOW (1.50)**	**MED (3.00)**	
	HIGH (3.25)	**HIGH (4.17)**			**MED (3.00)**	**MED (2.50)**			**HIGH (3.23)**

6. Medium unfavourable increase in *Percent Time in High Threat* (i.e. Safety).

It would seem, when pilgrims are moving with the same intention to reach the farthest inward position in the same round, the crowd becomes much more congested and produces an unfavourable impact on Tawaf performance. Therefore, a pilgrim population with normal distribution is better for Tawaf performance.

Third, a pilgrim population with uniform fast rate of spiralling inward has lower unfavourable impact on *Percent Time Distracted* (i.e., Satisfaction) and *Percent Time Exposed* (i.e., Health) than a slow rate of spiralling inward whereas a fast rate will have an extreme unfavourable impact on *Number of Neighbours*, *Number Gender Neighbours*, and safety. It would seem fast rate of inward spiralling increases congestion but allows the pilgrims to make fewer trajectory changes and be less exposed to infecting pilgrims. Therefore, a fast rate of spiralling significantly reduces the chance of being infected and being distracted.

Fourth, a 50% empty courtyard has the ability to contain the spread of high threat for highly congested crowd dynamics. Scenario 39 in Table 12 shows despite the extreme congestion, the *Percent Grids in High Threat* is less than 10%. Therefore, maintaining a 50% maximum pilgrim capacity for the Tawaf courtyard controls the spread of high threat situations.

Fifth, the highest crowd density at the cross-traffic matches the round in which the farthest spiral inward takes place. Figure 94, Figure 95, Figure 96, and Figure 97 (Appendix F) show that the high crowd density occurs closest to the Kaaba for scenario 39 (i.e., spiral farthest inward in round 1) and farthest from the Kaaba for scenario 42 (i.e., spiral farthest inward in round 4). Therefore, degree of spiralling inward matches the round in which the farthest inward spiralling takes place.

4.4 Validation

Although no model can claim it is 100% error free nor 100% fully matches the real system, this section attempts to provide a high degree of confidence that the TawafSIM model is programmed correctly and matches the real Tawaf crowd behaviour. Programming confidence is provided using code walkthrough, debugging walkthrough, unit testing, model logging, and rapid prototyping while matching real Tawaf crowd behaviour confidence is provided using practical validation, case approach validation, model calibration validation, and parameter sweeping validation.

4.4.1 Confidence in Programming

TawafSIM is written in Java and consists of eight classes with a total of approximately 4,500 lines of code. The steps to provide programming confidence include performing tests, identifying errors, correcting the code, and then starting again with testing. In particular, several techniques were used to identify errors in the code. First, the program was systematically walked through to attempt to ensure the code was written correctly and matched the design specifications for each algorithm. Second, a structured debugging walkthrough was conducted for test cases using the debugging feature of the Java integrated development environment, which traced program execution. Third, as the code was written, each method was tested individually; then groups of related methods were also tested. Fourth, model logging saved the key data for each agent for every time step of the simulation along with aggregate crowd and environment data for test cases, which was analysed using a spreadsheet to check agent behaviours and interaction between agents. Finally, three previous prototypes were developed each with incrementally more capabilities to finally develop TawafSIM in its final state.

4.4.2 Confidence in Matching Real Tawaf Crowd Behaviour

According to [29], ABMS often model complex social systems that cannot be subjected to controlled experiments to produce data to validate an ABMS. In such situations, the validation is subjective and attempts to show that the model produces sound insights and sound data based on a wide range of tests. This situation is also representative of modeling the Tawaf using the Tawaf ABMS.

4.4.2.1. Practical Validation

Practical validation involves validating the model's input, output, processes, and agent behaviours/interaction. First, TawafSIM uses specification data that is either officially available or is used by other modellers, which includes courtyard and pilgrim dimensions, number of pilgrims to perform Tawaf in a fixed duration, and pilgrim speed. Second, the assumptions made are either plausible or also made by others, which includes temporary circular barrier solution around the Kaaba to provide uniform crowd flow, limit maximum pilgrim capacity, and do not model Abraham Station, mob at Black Stone and non-courtyard Tawaf area. Third, the TawafSIM steps and internal flows correspond to the actual Tawaf ritual, which includes new pilgrims join crowd, existing pilgrims take their next step, and leave after seven rounds are complete. Fourth, the agent behaviours and agent interactions correspond to the real pilgrims, which includes spiral inward, maintain circle, and spiral outward based on pilgrim attributes/desires and local physical environment. Therefore, TawafSIM passes the practical validation tests.

4.4.2.2. Case Approach Validation

Case approach validation compares the 42 scenario simulations from TawafSIM with empirical Tawaf data, with other models, and with what is expected by subject matter experts. First, there is no current, comprehensive, reliable Tawaf performance data, which is available to the academic community. In [21] seven zones based on four GPS units were identified with different average velocities. However, this data is no longer valid as it was recorded when the Tawaf start line was painted on the floor. Since the study was made, the Tawaf line was removed because it caused significant delays at the Tawaf line as pilgrims tried to find the line in the middle of a dense crowd. As well, the study was based on only 4 GPS units, and the conditions surrounding the collection of the data are not provided. Thus, it is difficult to use a single metric for the seven regions to calibrate TawafSIM. This opinion is also supported in [37]. Additionally, the data in [21] is not applicable since TawafSIM models the proposed new Tawaf solutions to prevent the mob at the Black Stone and place a temporary circular barrier around the Kaaba. Therefore, there are limited opportunities to compare TawafSIM simulations to empirical data.

Second, there are no applicable models to compare to the 42 TawafSIM scenario observations. It is unreliable to validate TawafSIM with another un-validated Tawaf model. For instance, in [21], a round in the courtyard is 7.25 minutes, which is comparable to the simulation results in TawafSIM. Although the two models have similar results, the reference model is also not validated. Furthermore, comparing TawafSIM to non-Tawaf crowd simulations is not applicable. Using general pedestrian data from standard sources like Fruin [13] is not applicable since Fruin's data is for pedestrians walking on the sidewalk and assumes extremely low crowd densities. The applicability was also found not suitable for sporting events [39], and this was also the opinion in [37]. Therefore, Fruin's data is not applicable to validate the Tawaf pedestrian flow. Consequently, there are limited opportunities to compare TawafSIM simulations to existing models.

Third, there is an opportunity to compare TawafSIM scenario simulations with what is expected by subject matter experts. In particular, the Tawaf video during the 2011 Hajj season serves as the subject matter expert. The video shows that on the first day of Hajj when all the pilgrims are suppose to be in Mina, a temporary 10-foot rectangular barrier is placed around the Kaaba so workers can change its outer cloth. During this brief period, the Kaaba courtyard has about 20% of the courtyard full with people performing Tawaf around the temporary barrier around the Kaaba. Therefore, this situation is similar to what is modeled in TawafSIM, where the maximum pilgrim capacity is maintained and a temporary circular barrier is placed around the Kaaba to provide uniform circular motion. Although there is a significant difference in crowd dynamics using a rectangular versus circular barrier, there are useful observations from the video that can be used to compare the observations from TawafSIM. The video shows:

1. People performing Tawaf with approximately 50% empty space in the Tawaf crowd with additional pockets of empty space as well whereas the remaining courtyard is sparsely used for sitting and praying.

2. Crowd boundary starts closest to the Kaaba and grows outward by about 5 feet when approximately one third of the previous 5-foot region is full.
3. Most people move continuously at a fast pace of at least 2 feet per second.
4. People moving around the Abraham Station cause minimum flow disruption since ample space exists between people as they perform Tawaf.
5. Pilgrim flow is obstructed on the side opposite the Hateem due to the rectangular barrier shape and people watching the workers, which prevents natural crowd flow.

The video observations are similar to the TawafSIM simulation observations. Other than the three maximum pilgrim capacity scenarios, all the scenarios maintain the maximum pilgrim capacity to approximately 50% of the total Tawaf simulation area. As well, the TawafSIM crowd boundary algorithm grows the crowd boundary by 5 feet every time the previous crowd region is one third full. Additionally, other than the three speed scenarios, all the other scenarios set 75% of pilgrims to have speed of 2 or more feet per second. Furthermore, TawafSIM does not model the Abraham station since pilgrims can easily manoeuvre around it when there is 50% maximum pilgrim capacity. Finally, TawafSIM uses a circular barrier rather than a rectangular barrier, which provides an unobstructed pilgrim movement. Thus, the Tawaf video observations are similar to the TawafSIM simulation observations and provide some validation.

Consequently, comparing the 42 TawafSIM scenario simulations with empirical Tawaf data, with other models, and with what is expected by subject matter experts help validate TawafSIM.

4.4.2.3. Model Calibration Validation

TawafSIM calibrates the macro- and micro-movement algorithms to known Tawaf crowd dynamics. In particular, it is well known that pilgrims spiral inward farthest in the first few rounds then maintain that distance for a few rounds then spiral outward to the crowd boundary in a few rounds. As such, TawafSIM calibrates the movement algorithms so that the most aggressive pilgrims spiral inward within 1 round while the least aggressive pilgrims spiral inward within 3 rounds. Additionally, it is well known that the Tawaf crowd starts closest to the Kaaba and then grows outward as the number or pilgrims increases. Therefore, TawafSIM calibrates the scenarios to ensure that the Tawaf crowd grows naturally outward for all the different pilgrim attribute scenarios. Consequently, model calibration is used to validate that TawafSIM displays the well-known Tawaf crowd dynamics no matter what pilgrim attribute scenarios are simulated.

4.4.2.4. Parameter Sweeping Validation

Fifth, parameter sweeping generates the range of results and behaviours the model is capable of producing. In particular, the 42 TawafSIM scenario simulation observations show that TawafSIM produces sound implications and sound data. Therefore, parameter sweeping helps validate TawafSIM.

Consequently, the overall subjective practical validation, case approach validation, model calibration validation, and parameter sweeping validation tests show a high level of confidence that TawafSIM matches real Tawaf crowd behaviour.

4.5 Results

This section summarizes how crowd characteristics (i.e., gender, manners, speed, strength, desire to touch Kaaba, and spiralling inward), facility layout (i.e., circular entry access), and management preferences (i.e., pilgrim infecting level, pilgrim immunization level, rate of pilgrim entry, and maximum pilgrim capacity) impact emergent crowd behaviour and Tawaf performance during the Tawaf ritual. Figure 18, Figure 19, and Table 13 summarize the simulation observations to help identify the significant Tawaf crowd management implications from the 42 scenarios. Only scenarios 21, 41, and 42 (100% low speed along with 100% pilgrims spiral farthest inward on round 3 and 4) are excluded, as they do not meet the minimum required throughput of 27,778 pilgrims per hour to accommodate one third of the 4.0 million pilgrims performing Tawaf in the courtyard within the 48-hour period. This section discusses the TawafSIM results with respect to emergent crowd behaviour results and Tawaf performance results, which help develop guidelines for Tawaf crowd management.

4.5.1 Emergent Crowd Behaviour Results

The observations and analysis of the 42 scenarios help identify several noteworthy emergent crowd behaviours to better manage the Tawaf crowd.

1. The highest crowd density emerges at the cross traffic region, which is slightly inside the outer edge of the crowd boundary, not at the Tawaf start line or closest to the temporary Kaaba circular barrier.

Figure 18: List of critical scenarios impacting each Tawaf performance metric

Throughput (i.e., Pilgrims/hour)

1. Pilgrim speed (V. HIGH impact: 20,994 to 49,234)
2. Maximum pilgrim capacity (V. HIGH impact: 30,283 to 44,417)
3. Rate of pilgrim spiral inward (HIGH impact: 25,084 to 41,077)

Percent Time Distracted (i.e., Satisfaction)

4. Rate of pilgrim spiralling inward (HIGH impact: 27.60% to 41.30%)
5. Pilgrim speed (HIGH impact: 18.10% to 29.00%)
6. Maximum pilgrim capacity (MED impact: 27.60% to 31.30%)
7. Constant rate of pilgrim entry (MED impact: 22.20% to 29.00%)

Number of Neighbours (i.e., Satisfaction)

8. Rate of pilgrim spiralling inward (HIGH impact: 2.34 to 3.10)
9. Maximum pilgrim capacity (MED impact: 2.34 to 2.81)

Number of Gender Neighbours (i.e., Satisfaction)

10. Gender (V. HIGH impact: 0.00 to 0.90)
11. Rate of pilgrim spiralling inward (V. HIGH impact: 0.90 to 1.46)
12. Maximum pilgrim capacity (MED impact: 0.90 to 1.05)

Percent Time Exposed (i.e., Health)

13. Pilgrim-infecting level (V. HIGH impact: 4.95% to 13.00%)
14. Rate of spiralling inward (MED impact: 8.85% to 11.50%)
15. Pilgrim speed (MED impact: 7.65% to 11.85%)

Pilgrims per 900 ft^2 (i.e., Safety)

16. Pilgrim speed (HIGH impact: 390 to 489)
17. Rate of spiralling inward (MED impact: 390 to 518)
18. Maximum pilgrim capacity (MED impact: 390 to 466)

Percent Grids High Threats (i.e., Safety)

19. Maximum pilgrim speed (MED impact: 0% to 16%)

Percent Time High Threat (i.e., Safety)

20. Pilgrim speed (HIGH impact: 0% to 56%)
21. Maximum pilgrim capacity (HIGH impact: 0% to 55%)
22. Rate of spiralling inward (MED impact: 0% to 88%)

Figure 19: Summary of observations from each scenario

Gender: **Satisfaction (LOW)**

1. Male and female movement behaviour is same in single gender population.
2. Females are slightly more conservative in a mixed gender population.
3. Male dominant population is less distracted with fewer gender neighbours.

Rate of Pilgrim Entry: **Throughput (LOW), Satisfaction (LOW), Health (LOW)**

4. At 10 pilgrims/second rate there is a low unfavourable impact on throughput.
5. As constant rate of pilgrim entry increases (10 to 25 pilgrims/second) there is:
   a. Medium unfavourable increase in *Percent Time Distracted*
   b. Low unfavourable increase in *Number of Neighbours*
   c. Low unfavourable increase in *Percent Time Exposed*
6. At 25 pilgrims/second rate, micro-level congestion at the cross traffic increase but pilgrims autonomously disperse decreasing the macro-level congestion.
7. Increase in constant rate of pilgrim entry does not impact number of opposite gender neighbours at 50% empty courtyard.
8. When there is bursty pilgrim rate of entry there is:
   a. Medium favourable decrease in *Percent Time Distracted*
   b. Low favourable decrease in *Percent Time Exposed*
9. A long burst duration of 15 minutes results in less denser crowd closer to the Kaaba and a denser crowd at the cross traffic crowd boundary.

Circular Entry Access: **Throughput (LOW), Satisfaction (LOW)**

10. As the entry access increases from 25% to 100% there is:
    a. Low favourable increase in Throughput.
    b. Low favourable decrease in *Percent Time Distracted*.
11. Restricting the courtyard entry to 25% is the tipping point to unfavourably impact *Number Neighbours*, health, and *Pilgrims per 900 ft^2*.

Maximum Capacity: **Throughput (V. HIGH), Satisfaction (MED), Health (LOW), Safety (MED)**

12. As maximum pilgrim capacity increases from 25,000 to 40,000 there is:
    a. Very high favourable increase in Throughput
    b. Medium unfavourable increase in *Percent Time Distracted*
    c. Medium unfavourable increase in *Number Neighbours*
    d. Medium unfavourable increase in *Number Gender Neighbours*
    e. Low unfavourable increase in *Percent Time Exposed*
    f. Medium unfavourable increase in *Pilgrims per 900 ft^2*
    g. Medium unfavourable increase in *Percent Grids in High Threat*
    h. High unfavourable increase in *Percent Time in High Threat*
13. Limiting maximum pilgrim capacity to 82% of total Tawaf area and providing an unobstructed circular path limits high threat situations to 11%.
14. Extreme crowd capacity by itself does not significantly increase exposure to infecting individuals.
15. Safety tipping point when maximum capacity reaches 71% of total Tawaf area.
16. Emergent orthogonal crowd movement occurs when maximum pilgrim capacity reaches 72% of the maximum Tawaf area.

Figure 19: Summary of observations from each scenario

Pilgrim Manner: **No significant impact**

17. Low manner pilgrim population does not produce negative impact on Tawaf performance when the Tawaf courtyard is at 50% total capacity.
18. Higher manner individuals do not get higher level of satisfaction from being more considerate in their micro-movement decisions.

Pilgrim Speed Scenarios: **Throughput (V. High), Satisfaction (MED), Health (MED), Safety (MED)**

19. As pilgrim speed increases from 100% low to medium to high there is:
    a. Extreme favourable increase in Throughput
    b. High favourable decrease in *Percent Time Distracted*
    c. Low favourable decrease in *Number of Neighbours*
    d. Low favourable decrease in *Number of Gender Neighbours*
    e. Medium favourable decrease in *Percent Time Exposed*
20. A homogeneous speed distribution has an unfavourable impact on safety.
21. Pilgrims have an average speed lower than their maximum free flow speed.
22. Low speed has a dramatic unfavourable impact on safety.

Pilgrim Strength: **No significant impact**

23. A pilgrim population at any homogeneous strength level has a low favourable impact on *Number of Gender Neighbours* (i.e. Satisfaction).

Pilgrim Desire to Touch Kaaba: **Satisfaction (LOW)**

24. For a pilgrim population with homogenous desire to touch Kaaba, there is:
    a. Low unfavourable increase in *Percent Time Distracted*
    b. Low unfavourable increase in *Number Neighbours*
    c. Low favourable decrease in *Number Gender Neighbours*
    d. Low unfavourable increase in *Pilgrims per 900* ft^2

Pilgrim Infecting Level: **Health (V. HIGH)**

25. Pilgrim infecting level has very high impact on health.

Pilgrim Immunization Level: **No significant impact**

26. For a given percentage of infecting pilgrims performing Tawaf, increasing immunization level of susceptible pilgrims does not decrease their exposure to infecting pilgrims.

Pilgrim Degree Spiral-In: **Throughput (HIGH), Satisfaction (HIGH), Health (MED), Safety (MED)**

27. Spiralling inward sooner has favourable impact on Tawaf time and throughput.
28. A pilgrim population with homogenous pilgrim degree spiral-inward there is:
    a. High unfavourable increase in *Percent Time Distracted*
    b. High unfavourable increase in *Number Neighbours*
    c. Very high unfavourable increase in *Number Gender Neighbours*
    d. Medium unfavourable increase in *Pilgrims per 900* ft^2
    e. Low unfavourable increase in *Percent Grids in High Threat*
    f. Medium unfavourable increase in *Percent Time in High Threat*
29. Fast spiralling rate significantly reduces being infected and distracted.
30. Spread of high threat is avoided for congested crowd at 50% capacity.
31. Degree of spiralling inward influences location of cross traffic congestion.

2. In a single gender population, male and female pilgrims have the same emergent crowd dynamics whereas in a mixed gender population, female pilgrims are slightly more conservative then male pilgrims.
3. At 25 pilgrims per second rate of entry, the average micro-level congestion increases at the cross traffic region, but the pilgrims display emergent crowd behaviour to autonomously disperse faster, which decreases the maximum macro-level congestion.
4. For a bursty rate of pilgrim entry, non-uniform crowd dynamics emerge, which decrease distraction level and exposure to infecting pilgrims.
5. When the circular entry access is restricted from 100% to 50%, the pilgrims autonomously disperse to maintain almost the same Tawaf performance conditions.
6. When maximum pilgrim capacity reaches 72% of total Tawaf area, the safety-tipping point occurs for the percent of time courtyard grids are in high threat, which leads to emergent orthogonal crowd movement.
7. For a given percentage of infecting pilgrims performing Tawaf, increasing the immunization level of susceptible pilgrims does not decrease exposure to infecting pilgrims.
8. Extreme crowd conditions by themselves do not significantly increase exposure to infecting individuals.
9. Higher manner individuals slightly lower the overall level of satisfaction.
10. Pilgrims have an average speed lower than their maximum free flow speed.

4.5.2 Tawaf Performance Results

This sections summarizes the Tawaf performance results by discussing the results for the default scenario along with identifying which scenarios had the most impact on overall Tawaf performance and individual Tawaf metrics.

4.5.2.1. Default Scenario

The default scenario, which represents the most likely scenario for the ten simulation parameters, completes the 7 rounds of Tawaf in 50 minutes and generates above average Tawaf performance conditions:

- 30,283 pilgrims / hour (i.e., Throughput)
- 27.60% of the time distracted (i.e., Satisfaction)
- 2.34 neighbours / Moore neighbourhood (i.e., Satisfaction)
- 0.90 gender neighbours / Moore neighbourhood (i.e., Satisfaction)
- 8.85% of the time exposed to infecting pilgrims (i.e., Health)
- 390 maximum pilgrims per 900 ft^2 (i.e., Safety)
- 0% of grids in high threat (i.e., Safety)
- 0% time in high threat (i.e., Safety)

Only 3 of the above 8 metrics for the default scenario are significantly less favourable than other scenarios. First, default throughput of 30,283 pilgrims per hour is 39% lower then the highest value of 49,234 for scenario 23 (i.e., 100% high speed scenario). Second, default percent time distracted of 27.60% is 52% higher than the lowest value of 18.10% for scenario 23 (i.e., 100% high speed scenario). Third, default percent time exposed of 8.85% is 19% higher than lowest value of 7.45% for scenario 6 (i.e., 10 pilgrims per second). Therefore, the default scenario parameters provide above average Tawaf performance when compared to the other scenarios.

4.5.2.2. Scenarios Impacting Overall Tawaf Performance

Table 13 shows only three scenario categories have a significant impact (i.e. MED or higher impact) on overall Tawaf performance: rate of spiralling inward (HIGH), pilgrim speed (HIGH), and maximum pilgrim capacity (MED). First, if all the pilgrims spiral farthest inward in round 1, then there is a significant improvement in throughput but with almost the same significant decrease in satisfaction, health, and safety whereas the other homogeneous spiralling inward scenarios produce only unfavourable impact on all the Tawaf metrics. Second, for a high speed pilgrim population, there is significant favourable improvement for all metrics except for safety while for low speed there is only significant unfavourable impact. Third, as maximum pilgrim capacity increases, the throughput increases, but the other metrics are unfavourably impacted. Therefore, although three scenario categories have a significant impact on overall Tawaf performance, only the high speed scenario has a significant favourable impact on overall Tawaf performance.

4.5.2.3. Scenarios Impacting Individual Tawaf Metrics

Each Tawaf metric is significantly impacted by only a few of the scenario categories. Table 13 and Figure 18 show rate of spiralling inward has significant impact on 7 of the 8 metrics while pilgrim speed and maximum pilgrim capacity each have a significant impact on 6 metrics. Additionally, constant rate of pilgrim entry, gender, and pilgrim infecting level each have a significant impact on only one metric. Finally, the level of

Table 13: Summary of scenario impacts on Tawaf crowd performance.

<table>
<tr><th rowspan="2">SCENARIO</th><th>THROUGHPUT</th><th colspan="3">SATISFACTION</th><th>HEALTH</th><th colspan="3">SAFETY</th><th rowspan="2">IMPACT ON TAWAF</th></tr>
<tr><th>[Pilgrims/hr]</th><th>[% Time Distracted]</th><th>[# Neighbours]</th><th>[# Gender Neighbours]</th><th>[% Time Exposed]</th><th>[Pilgrims /900 ft^2]</th><th>[% Grids High Threat]</th><th>[% Time High Threat]</th></tr>
<tr><td rowspan="2">Spiral In</td><td rowspan="2">HIGH</td><td>HIGH</td><td>HIGH</td><td>V. HIGH</td><td rowspan="2">MED</td><td>MED</td><td>LOW</td><td>MED</td><td rowspan="2">HIGH</td></tr>
<tr><td colspan="3">HIGH</td><td colspan="3">MED</td></tr>
<tr><td rowspan="2">Speed</td><td rowspan="2">V. HIGH</td><td>HIGH</td><td>LOW</td><td>LOW</td><td rowspan="2">MED</td><td>HIGH</td><td>LOW</td><td>HIGH</td><td rowspan="2">HIGH</td></tr>
<tr><td colspan="3">MED</td><td colspan="3">MED</td></tr>
<tr><td rowspan="2">Max Pilgrims</td><td rowspan="2">V. HIGH</td><td>MED</td><td>MED</td><td>MED</td><td rowspan="2">LOW</td><td>MED</td><td>MED</td><td>HIGH</td><td rowspan="2">MED</td></tr>
<tr><td colspan="3">MED</td><td colspan="3">MED</td></tr>
<tr><td rowspan="2">Infecting</td><td rowspan="2">NO</td><td>NO</td><td>NO</td><td>NO</td><td rowspan="2">V. HIGH</td><td>NO</td><td>NO</td><td>NO</td><td rowspan="2">LOW</td></tr>
<tr><td colspan="3">NO</td><td colspan="3">NO</td></tr>
<tr><td rowspan="2">Rate of Entry</td><td rowspan="2">LOW</td><td>MED</td><td>LOW</td><td>NO</td><td rowspan="2">LOW</td><td>NO</td><td>NO</td><td>NO</td><td rowspan="2">LOW</td></tr>
<tr><td colspan="3">LOW</td><td colspan="3">NO</td></tr>
<tr><td rowspan="2">Circular Entry</td><td rowspan="2">LOW</td><td>LOW</td><td>NO</td><td>NO</td><td rowspan="2">NO</td><td>NO</td><td>NO</td><td>NO</td><td rowspan="2">NO</td></tr>
<tr><td colspan="3">LOW</td><td colspan="3">NO</td></tr>
<tr><td rowspan="2">Gender</td><td rowspan="2">NO</td><td>NO</td><td>NO</td><td>V. HIGH</td><td rowspan="2">NO</td><td>NO</td><td>NO</td><td>NO</td><td rowspan="2">NO</td></tr>
<tr><td colspan="3">LOW</td><td colspan="3">NO</td></tr>
<tr><td rowspan="2">Manners</td><td rowspan="2">NO</td><td>NO</td><td>NO</td><td>LOW</td><td rowspan="2">NO</td><td>NO</td><td>NO</td><td>NO</td><td rowspan="2">NO</td></tr>
<tr><td colspan="3">NO</td><td colspan="3">NO</td></tr>
<tr><td rowspan="2">Desire Touch</td><td rowspan="2">NO</td><td>LOW</td><td>LOW</td><td>LOW</td><td rowspan="2">NO</td><td>LOW</td><td>NO</td><td>NO</td><td rowspan="2">NO</td></tr>
<tr><td colspan="3">LOW</td><td colspan="3">NO</td></tr>
<tr><td rowspan="2">Strength</td><td rowspan="2">NO</td><td>NO</td><td>NO</td><td>LOW</td><td rowspan="2">NO</td><td>NO</td><td>NO</td><td>NO</td><td rowspan="2">NO</td></tr>
<tr><td colspan="3">NO</td><td colspan="3">NO</td></tr>
<tr><td rowspan="2">Immunization</td><td rowspan="2">NO</td><td>NO</td><td>NO</td><td>NO</td><td rowspan="2">NO</td><td>NO</td><td>NO</td><td>NO</td><td rowspan="2">NO</td></tr>
<tr><td colspan="3">NO</td><td colspan="3">NO</td></tr>
</table>

immunization for a given level of infecting pilgrims, strength, and manners has no significant impact on any of the metrics. Therefore, spiralling inward, pilgrim speed, and maximum pilgrim capacity each have a significant impact on at least 6 of the 8 Tawaf performance metrics.

4.5.3 Guidelines for Tawaf Crowd Management

The observations and analysis of the 42 scenarios help develop a set of guidelines to make Tawaf crowd management decisions leading to above average Tawaf performance.

1. Gender distribution for the pilgrim population does not have to be managed at any particular level. However, a dominant gender pilgrim population significantly decreases the number of opposite gender neighbours while a single gender population eliminates opposite gender neighbours.
2. Pilgrim rate of entry can fluctuate between 15 to 25 pilgrims per second. However, 15 pilgrims per second rate is optimum, and a rate of 10 pilgrims per second if necessary should be maintained for less than 15 minutes.
3. Courtyard circular entry access is optimum from 75% to 100% whereas 50% access will have low unfavourable impact on only throughput while 25% access will have low unfavourable impact on overall Tawaf performance.
4. Maximum pilgrim capacity is optimum (i.e., meets minimum throughput requirement with best conditions for satisfaction, health, and safety) at 25,000 pilgrims, which is 50% of total Tawaf area whereas 30,000 pilgrim capacity increases throughput moderately with unfavourable low impact on other metrics while pil-

grim capacity of 35,000 to 40,000 has very high increase on throughput with medium unfavourable impact on other metrics.

5. Limit maximum pilgrim capacity to 82% of total Tawaf area with unobstructed circular path to limit maximum grids in high threat to 11%.
6. Pilgrim manners, strength, and desire to touch the Kaaba do not have to be managed at any particular level since each has at most a low unfavourable impact limited only to satisfaction.
7. Maintain high pilgrim speed, which has a significant favourable impact on throughput, satisfaction, and health with a moderate unfavourable impact on safety whereas low pilgrim speed has a very high unfavourable impact on overall Tawaf performance.
8. Minimize percentage of infecting pilgrims through immunization and other infectious disease preventative measures to decrease the chance susceptible pilgrims get infected. However, for a given percentage of infecting pilgrims performing Tawaf, increasing the immunization level of susceptible pilgrims does not decrease their exposure to infecting pilgrims.
9. Decrease exposure to infecting pilgrims by increasing pilgrim speed, decreasing pilgrim rate of entry, and avoiding excess exposure by preventing homogenous low pilgrim speed and slow spiralling inward.
10. Avoid homogenous pilgrim population, which generally decreases Tawaf performance.

CHAPTER 5

TawafQT: Tawaf Waiting QT Model

This chapter describes in detail the Tawaf waiting area Queueing Theory (QT) model called TawafQT, which includes discussions on its objective, implementation, validation, numerical examples, and results.

5.1 Objective

The objective of TawafQT is to model the Tawaf waiting area to explore the impact of Tawaf pilgrim arrival process, Tawaf throughput, and management decisions on expected pilgrim arrival, departure, and waiting times along with the queue length during the Tawaf waiting period.

As discussed in the overview to the TawafDSS, potential changes to the Tawaf crowd management decisions with respect to shaping behaviour, changes to facility layout, or changes to management policies, would not only impact the Tawaf crowd dynamics but also the waiting time in the Tawaf areas. In particular, the new proposed Tawaf crowd management policy to limit the maximum number of pilgrims in the Tawaf courtyard makes it likely that pilgrims will have to wait in the Tawaf waiting area before it is their turn to perform the Tawaf ritual. In the past, this was not an issue because pilgrims would not be prevented from entering an already dense Tawaf courtyard; thus no significant queue of pilgrims resulted in the Tawaf waiting area. However, with the new proposed management policy, the objective of TawafQT is to accurately model the Tawaf waiting area to determine how long the pilgrims will have to wait before starting the Tawaf and how the queue length distribution will change under different pilgrim arrival and Tawaf throughout scenarios. Therefore, it is important to model the pilgrim waiting time in the Tawaf area as it impacts the overall Tawaf experience for the pilgrims.

5.2 Implementation

This section begins with an overview of the different types of QT models. Next the Minh model is described, followed by the description of TawafQT, which are the single- and two-server PH type service extensions to the Minh model.

5.2.1 QT Model Types

According to [26], QT has been extensively applied to the performance analysis of a wide range of systems. In some queueing systems, the model assumes the system has infinite population and operates indefinitely. For instance, many communication and traffic systems can be modeled with these assumptions because the flow of traffic is ongoing and normally exhibits steady state behaviour. In other queueing systems, the model assumes the system has finite population but operates indefinitely. For instance, the repair of machines in a factory can be modeled with these assumptions because there is a finite number of machines, which are served by repair crews when the machines breakdown periodically. Still in other queueing systems, the model assumes the system has finite population, which requires service only once. For instance, a typical grocery store can be modeled with these assumptions because roughly the same number of customers visit the store every day and require service only once. Furthermore, queueing systems that assume infinite population with indefinite operation have been studied extensively [16]. To a lesser extent, queueing systems from finite population and indefinite operation have also been studied [16] whereas queueing systems from finite population with single service have not been studied extensively.

Since the Tawaf waiting area has a finite population that requires service only once, Minh's discrete time, single-server queue from finite population requiring single service is used to model the Tawaf waiting area. First the Minh model is summarized, followed by the description of the TawafQT model represented as a single- and two-server PH type service extensions of the Minh model.

5.2.2 Minh Model

The Minh model [26] is applicable for queueing systems with a finite number of customers who each requires service only once. The system is observed at equally spaced epochs, $n \in \{0,1,2,\ldots\}$ where it is assumed arrivals, transfers from queue to service, and departures occur immediately prior to the epochs. The I identical and independent customers have the same time-dependent probability λ_n of arriving at the system immediately prior to epoch $n+1$ given that the customer has not arrived by epoch n. Since a customer only requires service once, the conditional probability that v customers will arrive immediately before epoch $n+1$ given that k customers have arrived at the system by epoch n is

$$g_{v,k}^{n} = \binom{I-k}{v} \left(1-\lambda_n\right)^{I-k-v} \quad (\lambda_n)^{v} \tag{1}$$

Additionally, the service time of the customers is the independent, identically distributed random variable S with $\Pr\{S=j\}=s_j,\ j \ge 1$. Furthermore, the queueing system is represented by the multivariate Markov chain $\{L_n, R_n, C_n; n \ge 0\}$, where, L_n is the number of customers in the queue and being served at epoch n, R_n is the residual service time of the customer being served at epoch n, and C_n is the number of customers who have arrived at the system by epoch n. Thus, the n-step transition probabilities of the chain are

$$P_{i,j,k}^{n} = \Pr\{L_n = i, R_n = j, C_n = k \mid L_0 = 0, R_0 = 0, C_0 = 0\}, \quad j \ge 0,\ 0 \le i \le k \le I \tag{2}$$

and the Chapman-Kolmogorov difference equations when $P_{0,0,0}^{0} = 1$ and $n \ge 0$ are

$$P_{0,0,0}^{n+1} = P_{0,0,0}^{n} g_{0,0}^{n} \tag{3}$$

$$P_{0,0,k}^{n+1} = P_{0,0,k}^{n} g_{0,k}^{n} + P_{1,1,k}^{n} g_{0,k}^{n}, \quad (1 \le k \le I) \tag{4}$$

$$P_{i,j,k}^{n+1} = \sum_{v=0}^{i-1} P_{i-v,j+1,k-v}^{n} g_{v,k-v}^{n} + \sum_{v=0}^{i} P_{i-v+1,1,k-v}^{n} g_{v,k-v}^{n} s_j + P_{0,0,k-i}^{n} g_{i,k-i}^{n} s_j, \ (1 \le i \le k-1,\ 2 \le k \le I,\ j \ge 1) \tag{5}$$

$$P_{k,j,k}^{n+1} = \sum_{v=0}^{k-1} P_{k-v,j+1,k-v}^{n} g_{v,k-v}^{n} + P_{0,0,0}^{n} g_{k,0}^{n} s_j, \ (1 \le k \le I,\ j \ge 1) \tag{6}$$

The probabilistic arguments for equations (3) to (6) are as follows. First, for equation (3), in order for the chain to be in state $\{0,0,0\}$ at epoch $n+1$, at epoch n, no customers are in the system, and there were no arrivals. Second, for equation (4), in order for the chain to be in state $\{0,0,k; 1 \le k \le I\}$ at epoch $n+1$, at epoch n, either the queue was empty and there were no arrivals; or the system had one customer in the queue with one unit of service left and there were no arrivals. Third, for equation (5), in order for the chain to be in state $\{i, j, k; (1 \le i \le k-1, 2 \le k \le I, j \ge 1\}$ at epoch $n+1$, at epoch n, one of the following three mutually exclusive alternatives must take place. One, the customer in service does not finish. As a result state $\{i, j, k\}$ can be reached if there are already i customers in the queue at epoch n and no arrivals occur; or $i-1$ customers are in the queue at epoch n and one arrival occurs; or continuing similarly up to one: one customers is in the queue at epoch n and $i-1$ arrivals occur. Two, the customer in service finishes. As a result state $\{i, j, k\}$ can be reached if there are already $i+1$ customers in the queue at epoch n, no arrivals occur, and service begins; or i customers are in the queue at epoch n, one arrival occurs, and service begins; or continuing similarly up to one: one customers is in the queue at epoch n, i arrivals occur, and service begins. Three, the queue is empty, i customers arrive, and service begins. Finally, for equation (6), in order for the chain to be in state $\{k, j, k; (1 \le k \le I, j \ge 1\}$ at epoch $n+1$, at epoch n either one of the following two mutually exclusive alternatives must take place. One, the customer in service does not finish. As a result state $\{k, j, k\}$ can be reached if there are already k customers in the queue at epoch n and no arrivals occur; or $k-1$ customers are in the queue at epoch n and one arrival occurs; or continuing similarly up to one: one customer is in the queue at epoch n and $k-1$ arrivals occur. Two, the queue is empty, k customers arrive, and service begins.

Although the complete information about the system can be obtained from equations (3) to (6) by calculating all the joint probabilities $P_{i,j,k}^{n+1}$ from $P_{i,j,k}^{n}$ and summing the appropriate values for the marginal distributions for arrival time, departure time, and queue length, the expected values are usually sufficient. First, the expected arrival epoch of the k^{th} customer is: $E[t_k] = \sum_{n=0}^{\infty}\sum_{j=0}^{k-1} T_j^n$, where $T_j^n = \Pr\{C_n = j\}$ is the probability exactly k customers have arrived up to and including time n. Second, the expected departure time of the i^{th} customer is: $E[d_i] = E[d_{i-1}] + E[s] + \sum_{n=0}^{\infty} P_{0,0,i-1}^n$, where $E[s]$ is the expected service time. Finally, the expected waiting time of the i^{th} customer is

$E[w_i] = (i-1)\,E[s] + \sum_{n=0}^{\infty}\sum_{j=0}^{i-1}(P_{0,0,j}^n - T_j^n)$.

5.2.3 TawafQT Single-Server PH Type Service Extension Model

Minh's model is enhanced by assuming when the service of a customer begins, it will last a period of time that has a PH type distribution [3, 28], which is a probability distribution represented by a random variable describing the time until absorption of an absorbing Markov chain with one absorbing state. As such, $R_n \approx PH(\alpha, T)$ of order J, where α is a vector and its entries are the probabilities the system starts from the non-absorbing states. As well, T is a matrix of order J and its entries are the probabilities of transitioning among the non-absorbing states with T^o is a vector and its entries are the probability of transitioning from the non-absorbing states to the absorbing state. Furthermore, $\alpha e = 1$, $Te + T^0 = e$, and e is a column vector of ones. Thus, the n-step transition probabilities of the chain are

$$P_{i,j,k}^n = \Pr\{L_n = i, R_n = j, C_n = k \mid L_0 = 0, R_0 = 0, C_0 = 0\},\ \ 1 \le j \le J,\ 0 \le i \le k \le I \qquad (7)$$

and the Chapman-Kolmogorov difference equations when $P_{0,0,0}^0 = 1$ and $n \ge 0$ are

$$P_{0,0,0}^{n+1} = P_{0,0,0}^{n} g_{0,0}^{n} \tag{8}$$

$$P_{0,0,k}^{n+1} = P_{0,0,k}^{n} g_{0,k}^{n} + \sum_{j_1=1}^{J} P_{1,j_1,k}^{n} g_{0,k}^{n} T_{j_1}^{o}, \quad (1 \le j_1 \le J, 1 \le k \le I) \tag{9}$$

$$\begin{aligned} P_{i,j_2,k}^{n+1} = &\sum_{v=0}^{i-1} \sum_{j_1=1}^{J} P_{i-v,j_1,k-v}^{n} g_{v,k-v}^{n} T_{j_1,j_2} + \sum_{v=0}^{i} \sum_{j_1=1}^{J} P_{i-v+1,j_1,k-v}^{n} g_{v,k-v}^{n} T_{j_1}^{o} \alpha_{j2} + P_{0,0,k-i}^{n} g_{i,k-i}^{n} \alpha_{j2}, \\ &(1 \le i \le k-1, 2 \le k \le I, 1 \le j_1, j_2 \le J) \end{aligned} \tag{10}$$

$$P_{k,j_2,k}^{n+1} = \sum_{v=0}^{k-1} \sum_{j_1=1}^{J} P_{k-v,j_1,k-v}^{n} g_{v,k-v}^{n} T_{j_1,j_2} + P_{0,0,0}^{n} g_{k,0}^{n} \alpha_{j_2}, (1 \le k \le I, 1 \le j_1, j_2 \le J) \tag{11}$$

Thus, the complete information about the system can be obtained from equations (8) to (11) by calculating all the joint probabilities $P_{i,j,k}^{n+1}$ from $P_{i,j,k}^{n}$. Note T , T^o, and α correspond to no service completion, service completion, and service begins respectively. The probabilistic arguments for equations (8) to (11) are the same as in the Minh model.

5.2.4 TawafQT Two-Server PH Type Service Extension Model

The PH type service extension to Minh's model in the previous subsection is extended to the case of two servers each with PH type service. The queueing system is represented by the multivariate Markov chain $\{L_n, R1_n, R2_n, C_n; n \ge 0\}$, where, L_n is the number of customers in the queue and being served at epoch n, $R1_n$ and $R2_n$ are the PH type service time of the customer being served in server one and two respectively at epoch n, and C_n is the number of customers that have arrived at the system by epoch n.

Let $R1_n \approx PH(\alpha, T)$ of order $J1$ and $R2_n \approx PH(\beta, S)$ of order $J2$, where $\alpha e = 1$, $Te + T^0 = e$, $\beta e = 1$, $Se + S^0 = e$, and e is a column vector of ones. Thus the *n*-step transition probabilities of the chain are

$$P^n_{i,j_1,j_2,k} = \Pr\{L_n = i, R1_n = j_1, R2_n = j_2, C_n = k \mid L_0 = 0, R1_0 = 0, R2_0 = 0,\ C_0 = 0\},$$
$$1 \le j_{11} \le J1,\ 1 \le j_{21} \le J2,\ \ 0 \le i \le k \le I \tag{12}$$

and the Chapman-Kolmogorov difference equations when $P^0_{0,0,0,0} = 1$ and $n \ge 0$ are

$$P^{n+1}_{0,0,0,0} = \left\lfloor P^n_{0,0,0,0} g^n_{0,0} \right\rfloor \tag{13}$$

$$\begin{aligned} P^{n+1}_{0,0,0,k} = {} & \left[P^n_{0,0,0,k} g^n_{0,k} \right] + \left[\sum_{j_1=1}^{J1} P^n_{1,j_1,0,k} g^n_{0,k} T^o_{j_1} \right] + \left[\sum_{j_2=1}^{J2} P^n_{1,0,j_2,k} g^n_{0,k} S^o_{j_2} \right] \\ & + \left[\sum_{j_1=1}^{J1} \sum_{j_2=1}^{J2} P^n_{2,j_1,j_2,k} g^n_{0,k} T^o_{j_1} S^o_{j_2} \right],\ (1 \le k \le I) \end{aligned} \tag{14}$$

$$\begin{aligned} P^{n+1}_{1,j_{12},0,k} = {} & \left[P^n_{0,0,0,k-1} g^n_{1,k-1} \alpha_{j_{12}} \varphi \right] + \left[\sum_{j_{11}=1}^{J1} P^n_{1,j_{11},0,k} g^n_{0,k} T_{j_{11},j_{12}} \right] \\ & + \left[\sum_{j_{11}=1}^{J1} P^n_{1,j_{11},0,k-1} g^n_{1,k-1} T^o_{j_{11},j_{12}} \alpha_{j_{12}} \varphi \right] + \left[\sum_{j_{21}=1}^{J2} P^n_{1,0,j_{21},k-1} g^n_{1,k-1} \alpha_{j_{12}} \varphi S^o_{j_{21}} \right] \\ & + \left[\sum_{j_{11}=1}^{J1} \sum_{j_{21}=1}^{J2} P^n_{2,j_{11},j_{21},k} g^n_{0,k} T_{j_{11},j_{12}} S^o_{j_{21}} \right] + \left[\sum_{j_{11}=1}^{J1} \sum_{j_{21}=1}^{J2} P^n_{2,j_{11},j_{21},k-1} g^n_{1,k-1} T^o_{j_{11}} \alpha_{j_{12}} \varphi S^o_{j_{21}} \right] \\ & + \left[\sum_{j_{11}=1}^{J1} \sum_{j_{21}=1}^{J2} P^n_{3,j_{11},j_{21},k} g^n_{0,k} T^o_{j_{11}} \alpha_{j_{12}} \varphi S^o_{j_{21}} \right],\ (1 \le j_{12} \le J1,\ 1 \le k \le I) \end{aligned} \tag{15a}$$

$$
\begin{aligned}
P^{n+1}_{1,0,j_{22},k} = & \left[P^n_{0,0,0,k-1} g^n_{1,k-1} \beta_{j_{12}} (1-\varphi)\right] \\
& + \left[\sum_{j_{21}=1}^{J2} P^n_{1,0,j_{21},k} g^n_{0,k} S_{j_{11},j_{12}}\right] \\
& + \left[\sum_{j_{21}=1}^{J2} P^n_{1,0,j_{21},k-1} g^n_{1,k-1} S^o_{j_{21}} \beta_{j_{22}} (1-\varphi)\right] \\
& + \left[\sum_{j_{11}=1}^{J1} P^n_{1,j_{11},0,k-1} g^n_{1,k-1} T^o_{j_{11}} \beta_{j_{22}} (1-\varphi)\right] \\
& + \left[\sum_{j_{11}=1}^{J1} \sum_{j_{21}=1}^{J2} P^n_{2,j_{11},j_{21},k} g^n_{0,k} T^o_{j_{11}} S_{j_{21},j_{22}}\right] \\
& + \left[\sum_{j_{11}=1}^{J1} \sum_{j_{21}=1}^{J2} P^n_{2,j_{11},j_{21},k-1} g^n_{1,k-1} T^o_{j_{11}} S^o_{j_{21}} \beta_{j_{22}} (1-\varphi)\right] \\
& + \left[\sum_{j_{11}=1}^{J1} \sum_{j_{21}=1}^{J2} P^n_{3,j_{11},j_{21},k} g^n_{0,k} T^o_{j_{11}} S^o_{j_{21}} \beta_{j_{22}} (1-\varphi)\right], \ (1 \le j_{21} \le J2, 1 \le k \le I)
\end{aligned}
\tag{15b}
$$

$$
\begin{aligned}
P^{n+1}_{i,j_{12},j_{22},k} = & \left[P^n_{0,0,0,k-i} g^n_{i,k-i} \alpha_{j_{12}} \beta_{j_{22}}\right] \\
& + \left[\sum_{j_{11}=1}^{J1} P^n_{1,j_{11},0,k-(i-1)} g^n_{i-1,k-(i-1)} T_{j_{11},j_{12}} \beta_{j_{22}} + \sum_{j_{21}=1}^{J2} P^n_{1,0,j_{21},k-(i-1)} g^n_{i-1,k-(i-1)} \alpha_{j_{12}} S_{j_{21},j_{22}}\right. \\
& \left. + \sum_{j_{11}=1}^{J1} P^n_{1,j_{11},0,k-i} g^n_{i,k-i} T^o_{j_{11}} \alpha_{j_{12}} \beta_{j_{22}} + \sum_{j_{21}=1}^{J2} P^n_{1,0,j_{21},k-i} g^n_{i,k-i} \alpha_{j_{12}} S^o_{j_{21}} \beta_{j_{22}}\right] \\
& + \left[\sum_{v=2}^{i} \left[\sum_{j_{11}=1}^{J1} \sum_{j_{21}=1}^{J2} P^n_{v,j_{11},j_{21},k-(i-v)} g^n_{i-v,k-(i-v)} T_{j_{11},j_{12}} S_{j_{21},j_{22}} + \sum_{j_{11}=1}^{J1} \sum_{j_{21}=1}^{J2} P^n_{v,j_{11},j_{21},k-(i-v+1)} g^n_{i-v+1,k-(i-v+1)} T^o_{j_{11}} \alpha_{j_{12}} S_{j_{21},j_{22}}\right.\right. \\
& \left.\left. + \sum_{j_{11}=1}^{J1} \sum_{j_{21}=1}^{J2} P^n_{v,j_{11},j_{21},k-(i-v+1)} g^n_{i-v+1,k-(i-v+1)} T_{j_{11},j_{12}} S^o_{j_{21}} \beta_{j_{22}} + \sum_{j_{11}=1}^{J1} \sum_{j_{21}=1}^{J2} P^n_{v,j_{11},j_{21},k-(i-v+2)} g^n_{i-v+2,k-(i-v+2)} T^o_{j_{11}} \alpha_{j_{12}} S^o_{j_{21}} \beta_{j_{22}}\right]\right] \\
& + \left[\sum_{j_{11}=1}^{J1} \sum_{j_{21}=1}^{J2} P^n_{i+1,j_{11},j_{21},k} g^n_{0,k} T^o_{j_{11}} \alpha_{j_{12}} S_{j_{21},j_{22}} + \sum_{j_{11}=1}^{J1} \sum_{j_{21}=1}^{J2} P^n_{i+1,j_{11},j_{21},k} g^n_{0,k} T_{j_{11},j_{12}} S^o_{j_{21}} \beta_{j_{22}}\right. \\
& \left. + \sum_{j_{11}=1}^{J1} \sum_{j_{21}=1}^{J2} P^n_{i+1,j_{11},j_{21},k-1} g^n_{1,k-1} T^o_{j_{11}} \alpha_{j_{12}} S^o_{j_{21}} \beta_{j_{22}}\right] \\
& + \left[\sum_{j_{11}=1}^{J1} \sum_{j_{21}=1}^{J2} P^n_{i+2,j_{11},j_{21},k} g^n_{0,k} T^o_{j_{11}} \alpha_{j_{12}} S^o_{j_{21}} \beta_{j_{22}}\right], \ (1 \le j_{11} \le J1, 1 \le j_{22} \le J2, 1 \le k \le I)
\end{aligned}
\tag{16}
$$

$$P^{n+1}_{k,j_{12},j_{22},k} = \left[P^n_{0,0,0,0} g^n_{k,0} \alpha_{j_{12}} \beta_{j_{22}}\right] + \left[\sum_{j_{11}=1}^{J1} P^n_{1,j_{11},0,1} g^n_{k-1,1} T_{j_{11},j_{12}} \beta_{j_{22}}\right] + \left[\sum_{j_{21}=1}^{J2} P^n_{1,0,j_{21},1} g^n_{k-1,1} \alpha_{j_{12}} S_{j_{21},j_{22}}\right]$$
$$+ \left[\sum_{v=2}^{k} \sum_{j_{11}=1}^{J1} \sum_{j_{21}=1}^{J2} P^n_{v,j_{11},j_{21},v} g^n_{k-v,v} T_{j_{11},j_{12}} S_{j_{21},j_{22}}\right], \ (1 \le j_{11} \le J1, 1 \le j_{22} \le J2, 2 \le k \le I, 2 \le i \le k-1) \tag{17}$$

The complete information about the system can be obtained from equations (13) to (17) by calculating all the joint probabilities $P^{n+1}_{i,j_1,j_2,k}$ from $P^n_{i,j_1,j_2,k}$. Note $T(S)$, $T^o(S^o)$, $\alpha(\beta)$, and ϕ correspond to no service completion in server one (two), service completion in server one (two), service begins in server one (two), and probability service begins with server one when both servers are empty respectively. The probabilistic arguments for equations (13) to (17) are as follows.

For equation (13), in order for the system to have no customers in the system at epoch $n+1$, at epoch n no customers are in the system and there were no arrivals.

For equation (14), in order for the system to have no customers in the queue when k customers have arrived by epoch $n+1$, at epoch n the following four mutually exclusive events must take place. First, the queue is empty and there are no arrivals. Second, there is one customer in server one, who finishes service and there are no arrivals. Third, there is one customer in server two, who finishes service and there are no arrivals. Fourth, there is one customer in each of the servers, who both finish and there is no arrival.

For equation (15a), in order for the system to have one customer in server one when k customers have arrived by epoch $n+1$, at epoch n the following seven mutually exclusive events must take place. First, the queue is empty and one customer arrives who goes to server one. Second, there is already one customer in server one who does not finish being served and there are no arrivals. Third, there is already one customer in server one who finishes service and one customer arrives who goes to server one. Fourth, there is one customer in server two who finishes service and one customer arrives who goes to server one. Fifth, there are two customers in the system with server two finishing service and no customers arrive. Sixth, there are two customers in the system with both servers finishing service and one customer arrives who goes to server one. Seventh, there are three customers in the system with both servers finishing, no arrivals, and the remaining customer in the queue goes to server one.

For equation (15b), in order for the system to have one customer in server two when k customers have arrived by epoch $n+1$, at epoch n the dual of the seven mutually exclusive events described in (15a) must take place.

For equation (16), in order for the queue to have i customers waiting for service (including the two customers being served) when k customers have arrived by epoch $n+1$, at epoch n the system could have started with between zero to $i+2$ customers in the system. Terms one, two, three, four, and five in (16) represent the situation where there are zero, one, two to i, $i+1$, and $i+2$ customers in the system respectively at epoch n. The details of the terms in (16) are relatively straightforward by reviewing the discussion for (15a).

For equation (17), in order for the queue to have k customers waiting for service (including the two customers being served) when k customers have arrived by epoch $n+1$, at epoch n no customers could have departed the system, which is represented by the four terms in (17).

5.3 Validation

This section describes the validation of the single-server PH type service extension models using the results from the Minh model. Both models are implemented in Matlab with equivalent parameters to compare results for expected customer arrival, departure, and waiting times (i.e. $E[t_k]$, $E[d_i]$, and $E[w_i]$). The two-server PH type service extension model is not being validated with the Minh model since the two-server equations for $E[t_k]$, $E[d_i]$, and $E[w_i]$ are difficult to develop when there are multiple parallel servers.

Minh's model is implemented with the geometric service distribution, $s_j = (1-p)^{j-1}p$, where $j \in \{1,2,3,\ldots,J\}$ and mean $\mu_{GEO} = 1/p$. TawafQT single-server PH type service extension model is implemented as PH(α, T) of order 2 with mean $\mu_{PH} = \alpha(I-T)^{-1}e$ as given in [3, 28].

Figure 20, 21, and 22 show expected customer arrival, departure, and waiting times respectively for both single-server models when $I = 3$ and $I = 10$ with equivalent parameters $\mu_{GEO} = \mu_{PH} = 1.7$, and $\lambda_n = \lambda = 0.3$. Furthermore, the parameters used for the PH type distribution is $T = \begin{bmatrix} 0.0597 & 0.3276 \\ 0.0297 & 0.3886 \end{bmatrix}$ and $\alpha = [0.4 \quad 0.6]$.

Figure 20, 21, and 22 show both single-server models produce almost the same results for $E[t_k]$, $E[d_i]$, and $E[w_i]$ for both $I = 3$ and $I = 10$. In particular, shows both single-server models have the exact same expected customer arrival times for both $I = 3$ and $I = 10$ since $E[t_k]$ only depends on the common values of I and λ in the calculation for $g_{v,k}^n$. Figure 21 and 22 show a negligible difference between Minh model and single-

Figure 20: Validation of single-server models using expected arrival times

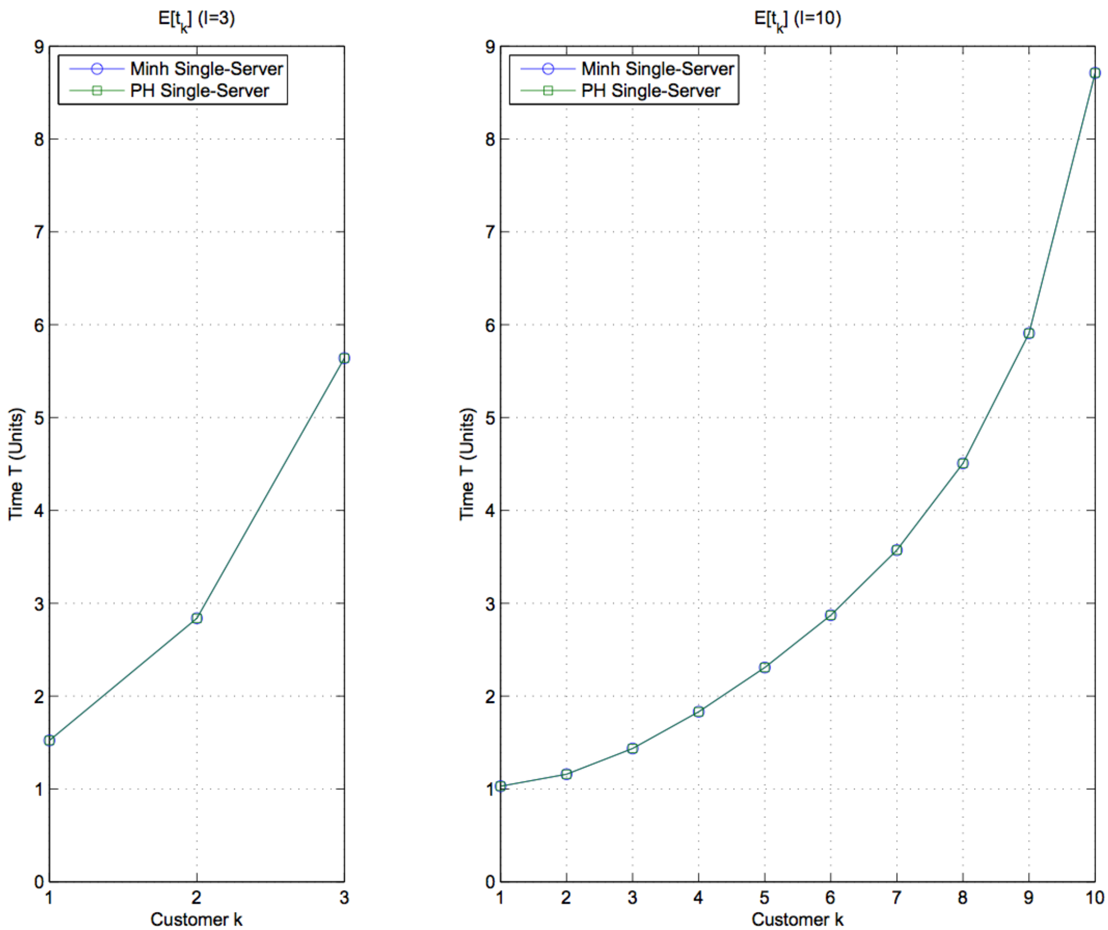


Figure 21: Validation of single-server models using expected departure times

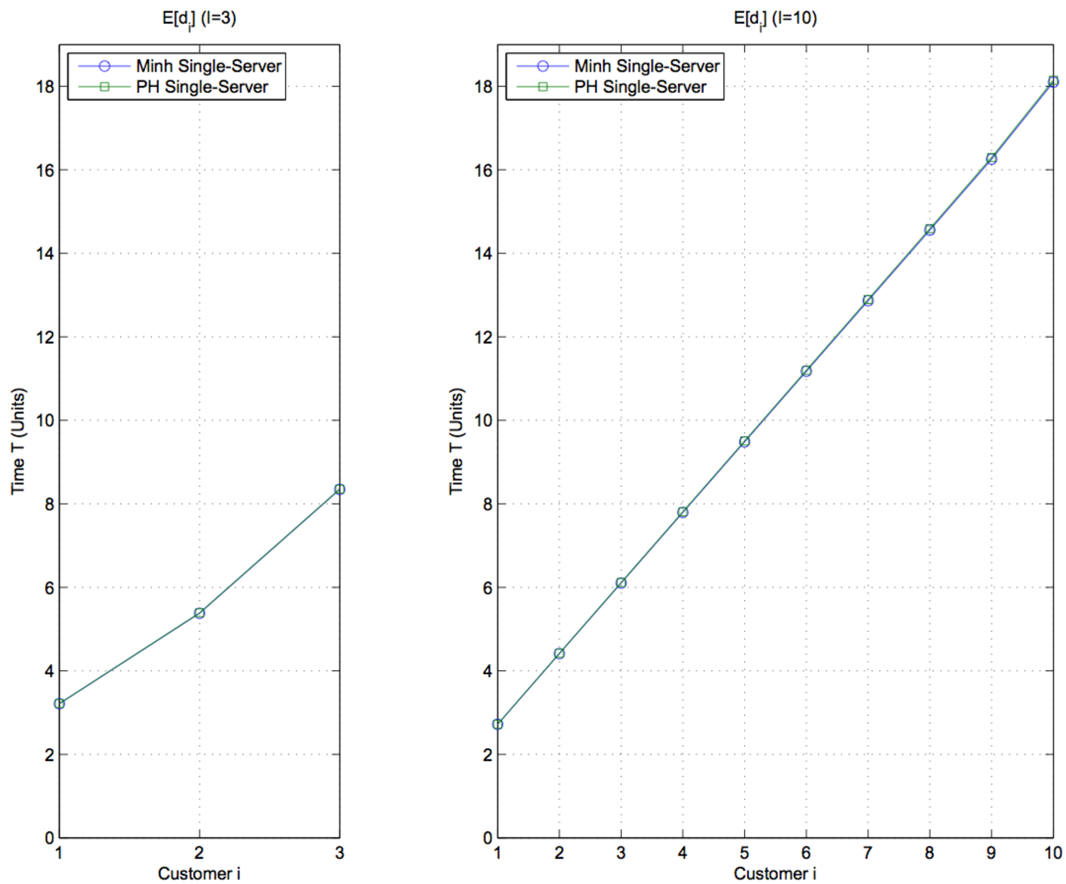
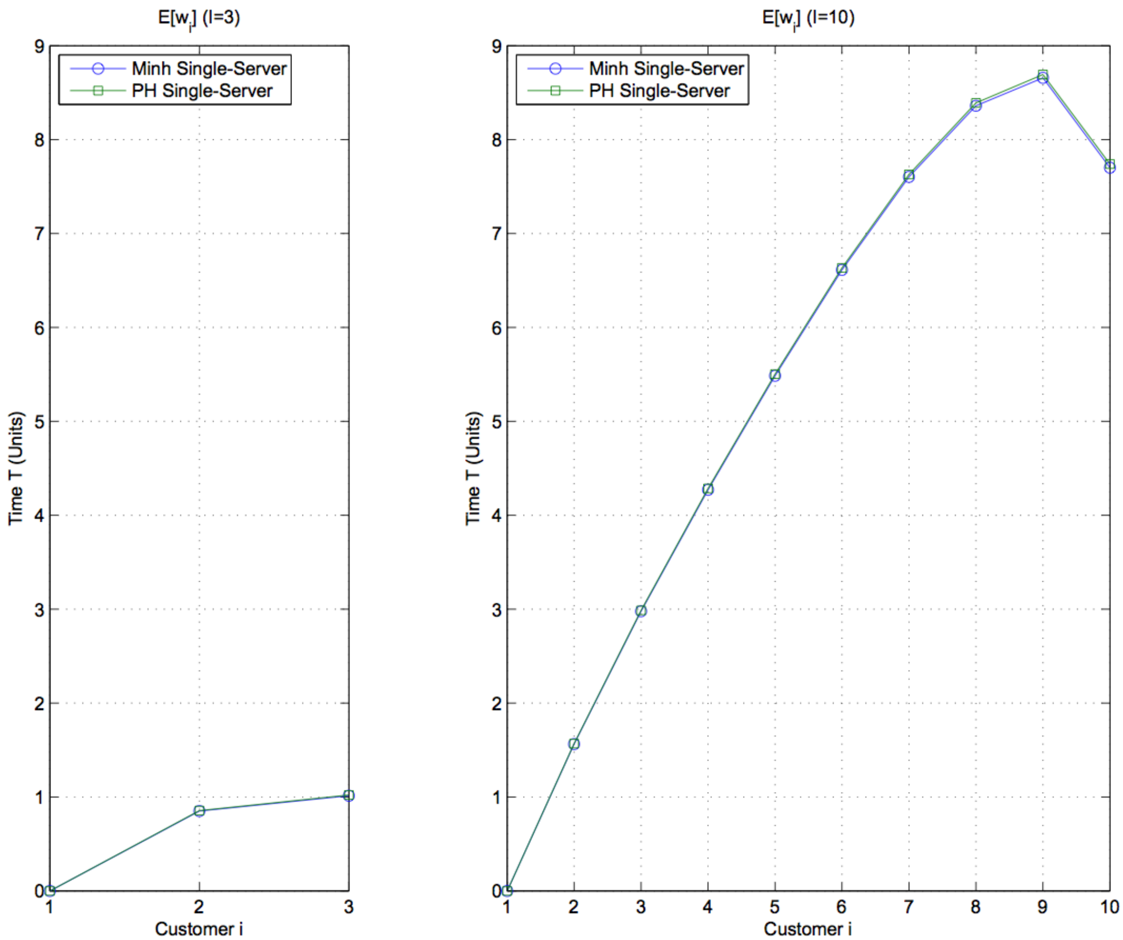


Figure 22: Validation of single-server models using expected waiting times



server PH extension model for $I = 10$ because the geometric service distribution in the Minh model is truncated at $J = 14$ elements since dimension of the P matrix becomes too large for Matlab to compute, which results in slightly imprecise probability values that get compounded as I increases.

Finally, since both models validate each other, the single-server PH Type service extension model is used exclusively for the numerical examples in section 5.4 since it is computationally faster and more precise than the truncated Minh model.

5.4 Numerical Examples

This section helps understand how the Tawaf waiting area behaves under different pilgrim arrival and Tawaf throughput conditions in order to choose Hajj crowd management decisions to minimize pilgrim waiting time and queue length in the Tawaf waiting area while processing all the pilgrims during the 48-hour Tawaf duration in the Kaaba courtyard.

5.4.1 Constraints

Recall that approximately 1.4 million pilgrims must perform Tawaf in the courtyard within the required 48-hour period, which is approximately one third of the total 4 million annual pilgrims. To manage this large crowd, consider 4 equal periods of 12-hours, where each period must accommodate 350,000 pilgrims. Furthermore, assume for logistic reasons the pilgrims are batched into 10 large groups of 35,000 each in order to transport them from Mina to Mecca to perform the Tawaf.

Additionally, the arrival of the 10 customer groups from Mina to Mecca depends on many factors, including pilgrim preference and transportation system capacity via train, bus, pedestrian walkway, and aerial ropeway transit in the near future [8]. Nevertheless, consider pilgrim group arrival probability λ_n of arriving at the Tawaf waiting area in the range of 0.1 to 0.3, which as shown later allows all the pilgrim groups to arrive slowly within 12 hours to quickly within 5 hours respectively.

Furthermore, the Tawaf waiting area is modeled as a first-come-first-served queue. As such, the customer group at the start of the Tawaf waiting area queue is served (i.e., transitions from the start of the Tawaf waiting area to the Tawaf courtyard) at the same rate as the Tawaf throughput in the Kaaba courtyard as determined by TawafSIM. Therefore, the fastest (optimistic) Tawaf waiting area service time is 30 minutes (i.e., 49,234 pilgrims per hour from TawafSIM scenario 23) while the most likely and slowest (pessimistic) service times are 50 minutes (i.e., 30,283 pilgrims per hour from TawafSIM scenario 1) and 70 minutes (i.e., 20,994 pilgrims per hour from TawafSIM scenario 21) respectively. These Tawaf waiting area service times correspond to a queueing model with 25,000 (i.e., the maximum capacity in the Tawaf courtyard) servers and individual pilgrim customers. Since TawafQT uses a single server with group size of 35,000 pilgrims, the adjusted Tawaf waiting area service times are 42 minutes for optimistic scenario (i.e., 30 / 25,000 * 35,000), 70 minutes for most likely scenario, and 98 minutes for pessimistic scenario.

Finally, although three different unrelated T matrices used for the PH type service distributions can be selected such that their mean is equal to one of the above adjusted Tawaf waiting area service times, it is better to select a single parent T matrix which is then scaled by θ, where $0 < \theta < 1$, to produce a family of related T matrices from which children matrices are chosen with a mean equal to one of the above adjusted service times. As such, the parent $T = \begin{bmatrix} 0.5905 & 0.2445 \\ 0.0450 & 0.7900 \end{bmatrix}$ is selected which has a $\mu = 6.06$ and produces a family of related $T\,(\theta) = \begin{bmatrix} \theta T_{11} & \theta T_{12} \\ \theta T_{21} & \theta T_{22} \end{bmatrix}$ matrices with $1.00 < \mu_\theta < \mu$ for $0 < \theta < 1$. Since the adjusted service times are in the range 42 minutes to 98 minutes, the time unit for the $T\,(\theta)$ matrices is multiplied by 30 minutes. Thus, the scaled adjusted services times for the Tawaf waiting area are 1.40 time units for optimistic scenario (i.e., 42 minutes / 30), 2.34 time units for most likely scenario, and 3.26 time units for pessimistic scenario. As such the following $T\,(\theta)$ matrices have the required scaled adjusted service times for the Tawaf waiting area, which are used in the numerical examples below.

$$T\,(0.345) = \begin{bmatrix} 0.2037 & 0.0844 \\ 0.0155 & 0.2726 \end{bmatrix}, \qquad \mu_{0.345} = 1.4046$$

$$T\,(0.685) = \begin{bmatrix} 0.4045 & 0.1675 \\ 0.0308 & 0.5412 \end{bmatrix}, \qquad \mu_{0.685} = 2.3363$$

$$T\,(0.830) = \begin{bmatrix} 0.4901 & 0.2029 \\ 0.0374 & 0.6557 \end{bmatrix}, \qquad \mu_{0.830} = 3.2579$$

5.4.2 Example 1: Optimistic Tawaf Throughput

Numerical example 1a to 1d assumes the Tawaf courtyard has the highest throughput rate during a 12-hour period (which results in the shortest scale adjusted Tawaf waiting area service time of 1.4 time units) and varies the pilgrim group arrival rate from 0.1 to 0.3 to see the impact on waiting time and queue length over the 12-hour period.

Figure 23 shows the results for homogeneous pilgrim customer arrival rate of $\lambda_n = \lambda = 0.1$. The plots for T_i^n and $E\ [t_i]$ show that not only are the 10 pilgrim groups expected to arrive throughout the 12-hour period with a large spread, but also the inter-arrival time increases from 30 minutes to over 4 hours by the last arrival. As well the plot for $E\ [d_i]$ shows the last pilgrim group is not expected to finish within the 12-hour period after the first group arrives due to the significant spread of the arrivals. Finally, the plot for $E\ [w_i]$ shows the expected waiting time for each pilgrim group is less than 1 hour since the queue length is expected to be short. For instance, the queue length tail distribution shows the probability of queue length greater than 2 is approximately 0.1.

Figure 24 shows the results for homogeneous pilgrim customer arrival rate of $\lambda_n = \lambda = 0.2$. The plots for T_i^n and $E\ [t_i]$ show all 10 pilgrim groups are expected to arrive within the first 7 hours with a moderate spread and an inter-arrival time which increases from 12 minutes to approximately 60 minutes by the ninth arrival. As well the plot for $E\ [d_i]$ shows the inter-departure time is approximately the expected service time for all the pilgrim groups except the last group, which means the server is almost never idle. Additionally, the plot for $E\ [w_i]$ shows the expected waiting time for subsequent pilgrim group increases up to a maximum of approximately 2 hours. Finally, the queue length tail distributions shows the queue length is expected to be longer than in example 1a.

Figure 25 shows the results for homogeneous pilgrim customer arrival rate of $\lambda_n = \lambda = 0.3$. The plots for T_i^n and $E\ [t_i]$ show all 10 pilgrim groups are expected to arrive within the first 5 hours with a narrow spread and an inter-arrival time which increases from 6 minutes to approximately 42 minutes by the ninth arrival. As well the plot for

$E\ [d_i]$ shows the inter-departure time is almost exactly the expected service time for all the pilgrim groups except the last group, which means the server is never idle. Additionally, the plot for $E\ [w_i]$ shows the expected waiting time for subsequent pilgrim group increases up to a maximum of approximately 3 hours. Finally, the queue length tail distributions shows the queue length is expected to be longer than in example 1b.

Figure 26 shows the results for inhomogeneous pilgrim customer arrival rate of $\lambda_n = 0.1$ for $0 \leq n \leq 14$ and $\lambda_n = 0.3$ for $15 \leq n \leq 24$. All the plots are similar to example 1a (i.e. $\lambda_n = 0.1$) for the first 7 pilgrim groups. Since the expected arrival time for the last three pilgrim groups is influenced by the larger arrival rate (i.e. $\lambda_n = 0.3$), the last three pilgrim groups are expected to arrive significantly earlier than in example 1a. As such, all 10 pilgrim groups are able to depart within the 12 hour period while maintaining the same small wait time and queue length as in example 1a.

5.4.3 Example 2: Most likely Tawaf Throughput

Numerical example 2 assumes the Tawaf courtyard has the default throughput rate during a 12-hour period (i.e. expected Tawaf waiting area scale adjusted service time is 2.3 time units) and varies the pilgrim group arrival rate from 0.1 to 0.3 to see the impact on waiting time and queue length over a 12-hour period.

The explanations of the results for example 2a to 2d follow the explanations for example 1a to 1d. As anticipated, Figure 27, Figure 28, Figure 29, and Figure 30 show since the expected pilgrim group arrival times in example 2a to 2d are the same as in their corresponding example 1 scenarios, a longer expected service time in example 2 scenarios causes the expected waiting time and queue length to be longer.

5.4.4 Example 3: Pessimistic Tawaf Throughput

Numerical example 3 assumes the Tawaf courtyard has the pessimistic throughput rate during a 12-hour period (which results in the longest Tawaf waiting area scale adjusted service time of 3.3 time units) and varies the pilgrim group arrival rate from 0.1 to 0.3 to see the impact on waiting time and queue length over a 12-hour period.

Similar to example 2, the explanations of the results for example 3a to 3d follow the explanations for example 1a to 1d. As anticipated, Figure 31**,** Figure 32**,** Figure 33**,** and Figure 34 not only show the longer expected service time in example 3 scenarios cause the expected waiting time and queue length to be longer than in example 2, but the expected departure times in example three can not finish during the 12 hour period.

5.5 Results

This section summarizes the numerical example findings in a guideline document format to show how Tawaf pilgrim group arrival probability and Tawaf throughput will impact pilgrim group departure and waiting times along with the queue length in the Tawaf waiting area.

1. [Example 1a] In a 12-hour period where the average Tawaf time is 30 minutes, if the pilgrim group, transportation system, or scheduling system result in a homogeneous pilgrim group arrival rate of $\lambda = 0.1$ then the last pilgrim group will begin their Tawaf on 15.0 hour of the 12-hour period with a maximum pilgrim group waiting time of 53 minutes, an average waiting time of approximately 34 minutes, and an average queue length of 0.96 pilgrims.

2. [Example 1b] In a 12-hour period where the average Tawaf time is 30 minutes, if the pilgrim group, transportation system, or scheduling system result in a homogeneous pilgrim group arrival rate of $\lambda = 0.2$ then the last pilgrim group will begin their Tawaf on 8.8 hour of the 12-hour period with a maximum waiting time of 2.2 hours, an average waiting time of 1.4 hours, and an average queue length of 1.68 pilgrims.
3. [Example 1c] In a 12-hour period where the average Tawaf time is 30 minutes, if the pilgrim group, transportation system, or scheduling system result in a homogeneous pilgrim group arrival rate of $\lambda = 0.3$ then the last pilgrim group will begin their Tawaf on 7.8 hour of the 12-hour period with a maximum waiting time of approximately 3.2 hours, an average waiting time of approximately 2.0 hours, and an average queue length of 2.18 pilgrims.
4. [Example 1d] In a 12-hour period where the average Tawaf time is 30 minutes, if the pilgrim group, transportation system, or scheduling system result in an inhomogeneous pilgrim group arrival rate of $\lambda = 0.1$ for first 7 hours then $\lambda = 0.3$ for remaining 5 hours then the last pilgrim group will begin their Tawaf on 10.5 hour of the 12-hour period with a maximum waiting time of 54 minutes, an average waiting time of 37 minutes, and an average queue length of 1.05 pilgrims.
5. [Example 2a] In a 12-hour period where the average Tawaf time is 50 minutes, if the pilgrim group, transportation system, or scheduling system result in a homogeneous pilgrim group arrival rate of $\lambda = 0.1$ then the last pilgrim group will begin their Tawaf on the 16.5 hour of the 12-hour period with a maximum pilgrim

group waiting time of 2.9 hours, an average waiting time of approximately 1.9 hours, and an average queue length of 2.19 pilgrims.

6. [Example 2b] In a 12-hour period where the average Tawaf time is 50 minutes, if the pilgrim group, transportation system, or scheduling system result in a homogeneous pilgrim group arrival rate of $\lambda = 0.2$ then the last pilgrim group will begin their Tawaf on the 12.5 hour of the 12-hour period with a maximum pilgrim group waiting time of 5.4 hours, an average waiting time of approximately 3.4 hours, and an average queue length of 3.47 pilgrims.
7. [Example 2c] In a 12-hour period where the average Tawaf time is 50 minutes, if the pilgrim group, transportation system, or scheduling system result in a homogeneous pilgrim group arrival rate of $\lambda = 0.3$ then the last pilgrim group will begin their Tawaf on the 12.3 hour of the 12-hour period with a maximum pilgrim group waiting time of 6.9 hours, an average waiting time of approximately 4.1 hours, and an average queue length of 4.07 pilgrims.
8. [Example 2d] In a 12-hour period where the average Tawaf time is 50 minutes, if the pilgrim group, transportation system, or scheduling system result in an inhomogeneous pilgrim group arrival rate of $\lambda = 0.1$ for first 7 hours then $\lambda = 0.3$ for remaining 5 hours then the last pilgrim group will begin their Tawaf on 13.0 hour of the 12-hour period with a maximum waiting time of 3.1 hours, an average waiting time of 2.1 hours, and an average queue length of 2.44 pilgrims.
9. [Example 3a] In a 12-hour period where the average Tawaf time is 70 minutes, if the pilgrim group, transportation system, or scheduling system result in a homogeneous pilgrim group arrival rate of $\lambda = 0.1$ then the last pilgrim group will

begin their Tawaf on the 19.0 hour of the 12-hour period with a maximum pilgrim group waiting time of 5.5 hours, an average waiting time of approximately 3.5 hours, and an average queue length of 3.17 pilgrims.

10. [Example 3b] In a 12-hour period where the average Tawaf time is 70 minutes, if the pilgrim group, transportation system, or scheduling system result in a homogeneous pilgrim group arrival rate of $\lambda = 0.2$ then the last pilgrim group will begin their Tawaf on the 16.9 hour of the 12-hour period with a maximum pilgrim group waiting time of 9.0 hours, an average waiting time of approximately 5.4 hours, and an average queue length of 4.67 pilgrims.
11. [Example 3c] In a 12-hour period where the average Tawaf time is 70 minutes, if the pilgrim group, transportation system, or scheduling system result in a homogeneous pilgrim group arrival rate of $\lambda = 0.3$ then the last pilgrim group will begin their Tawaf on the 4.4 hour of the 12-hour period with a maximum pilgrim group waiting time of 16.9 hours, an average waiting time of approximately 6.2 hours, and an average queue length of 5.30 pilgrims.
12. [Example 3d] In a 12-hour period where the average Tawaf time is 70 minutes, if the pilgrim group, transportation system, or scheduling system result in an inhomogeneous pilgrim group arrival rate of $\lambda = 0.1$ for first 7 hours then $\lambda = 0.3$ for remaining 5 hours then the last pilgrim group will begin their Tawaf on 7.5 hour of the 12-hour period with a maximum waiting time of 6.5 hours, an average waiting time of 4.0 hours, and an average queue length of 3.48 pilgrims.

Figure 23: Numerical example 1a

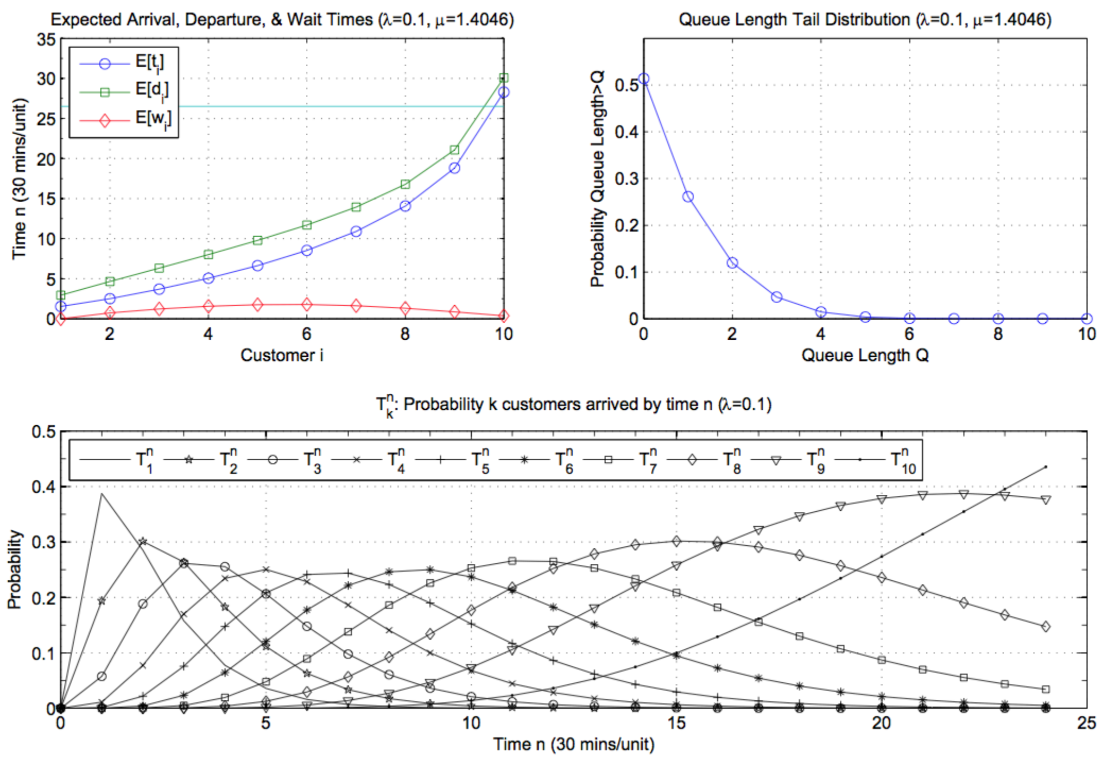


Figure 24: Numerical example 1b

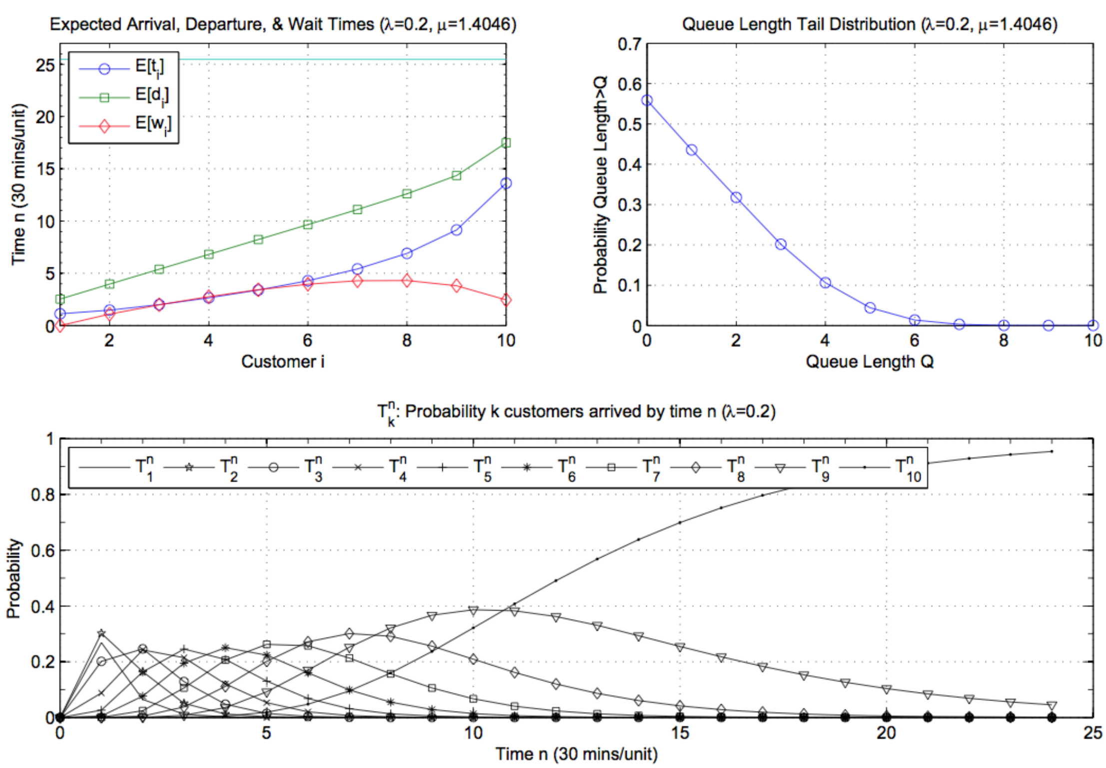


Figure 25: Numerical example 1c

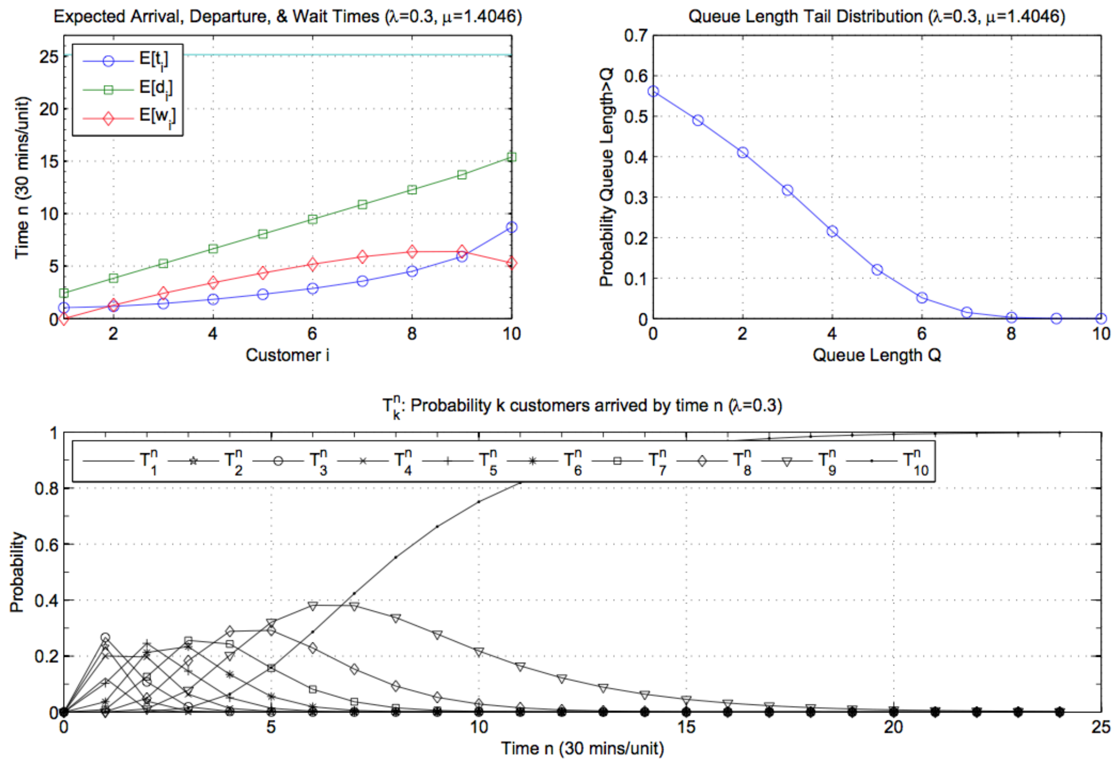


Figure 26: Numerical example 1d

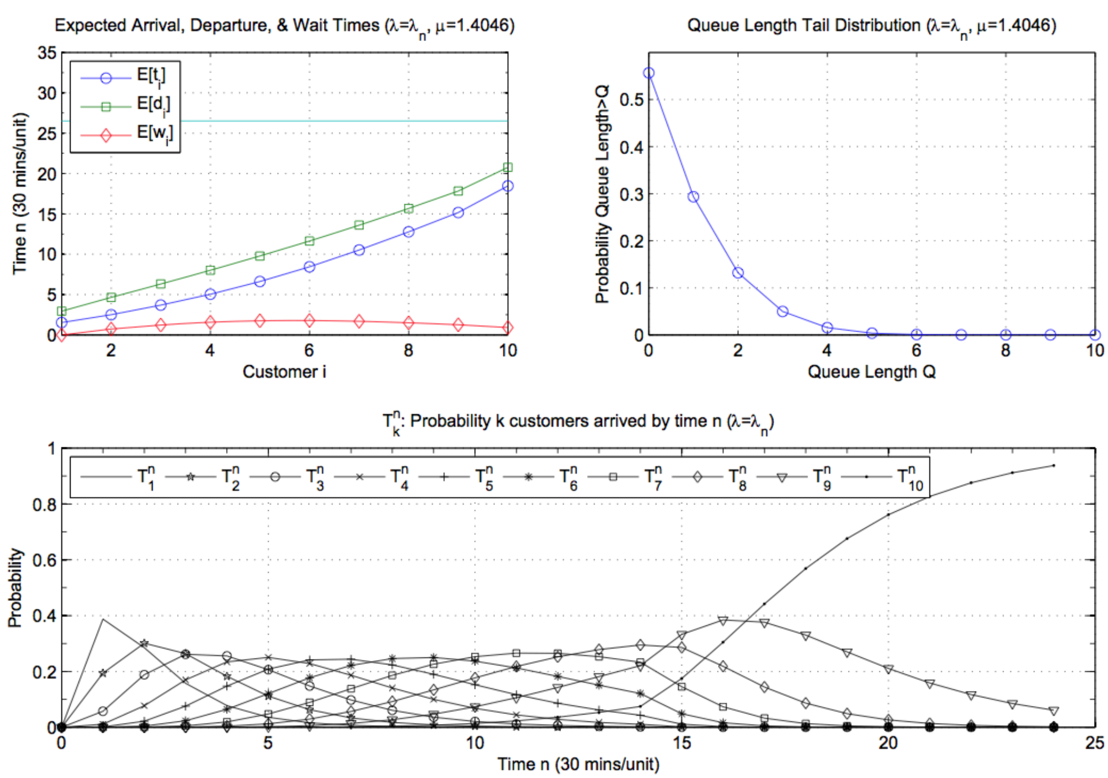


Figure 27: Numerical example 2a

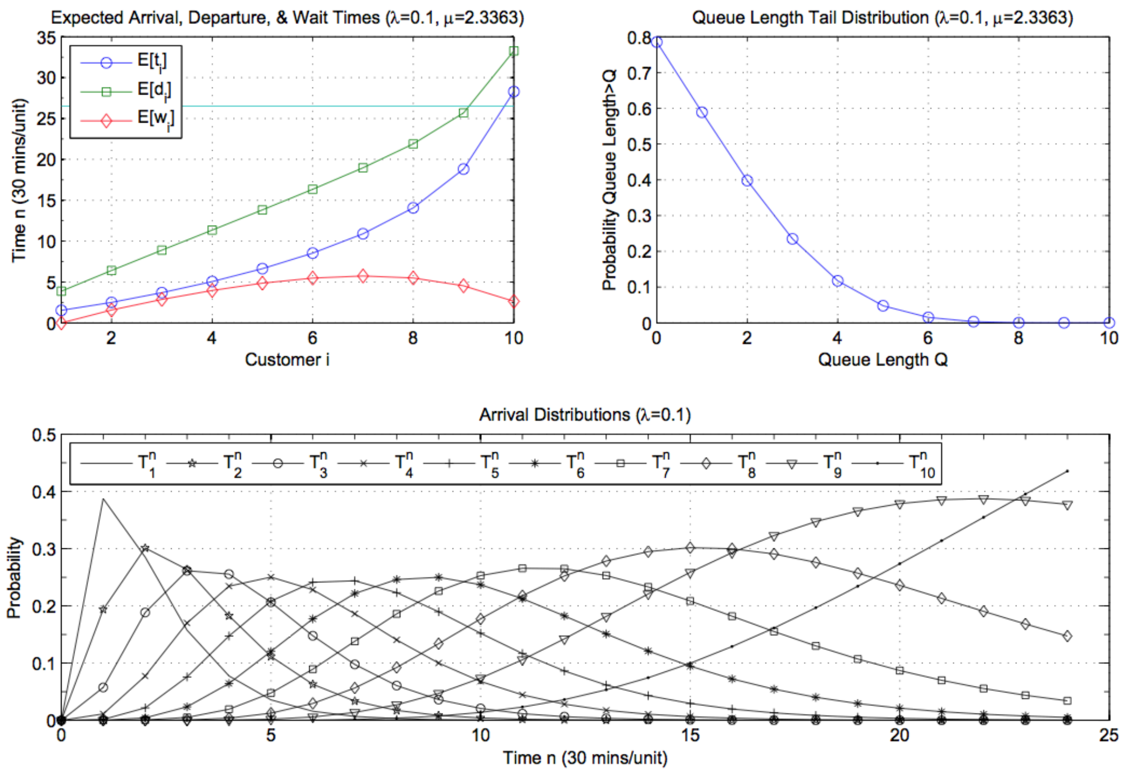


Figure 28: Numerical example 2b

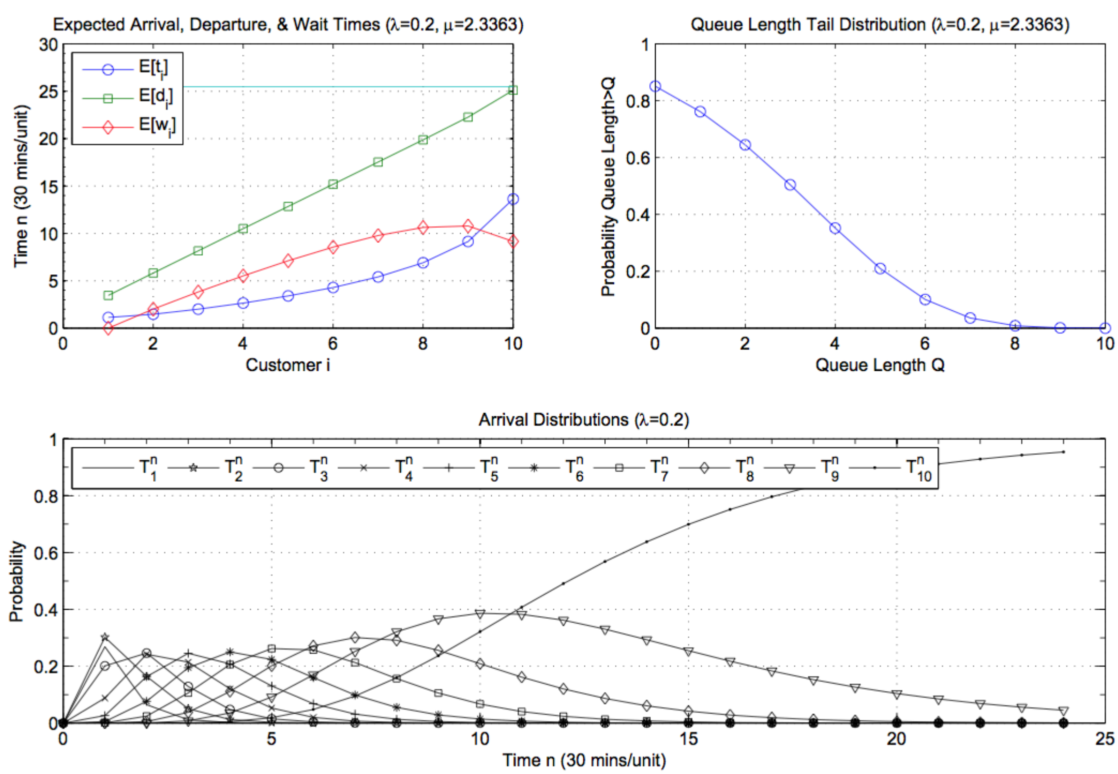


Figure 29: Numerical example 2c

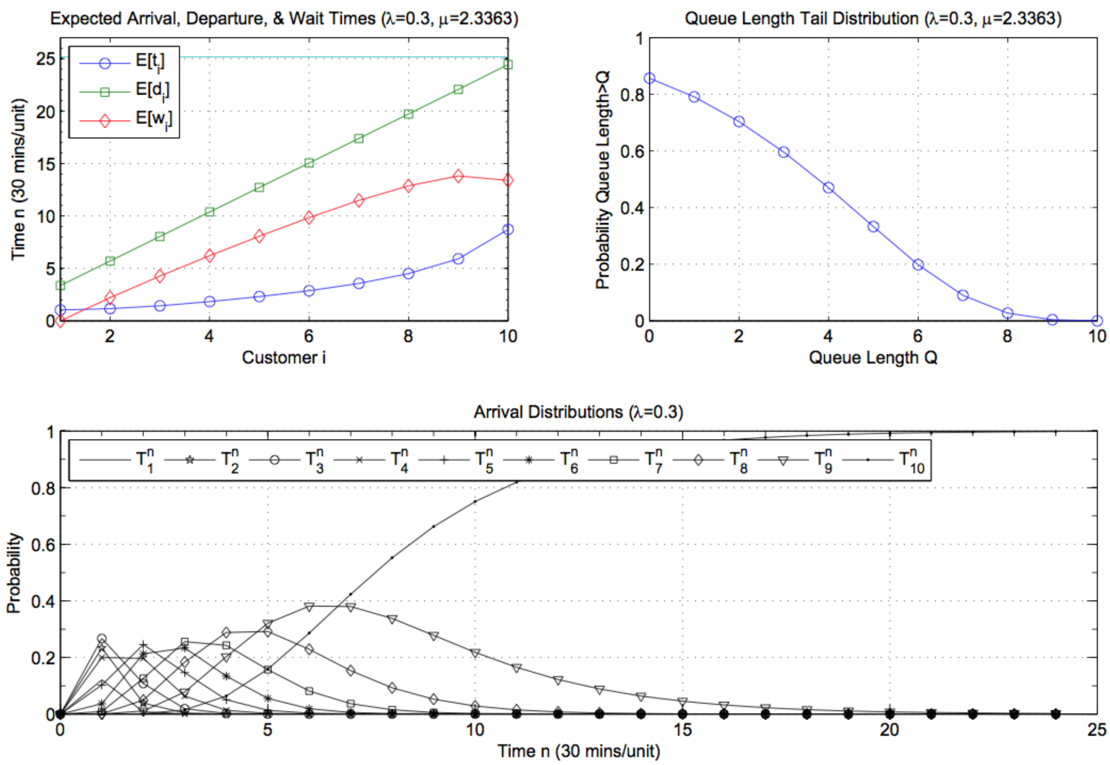


Figure 30: Numerical example 2d

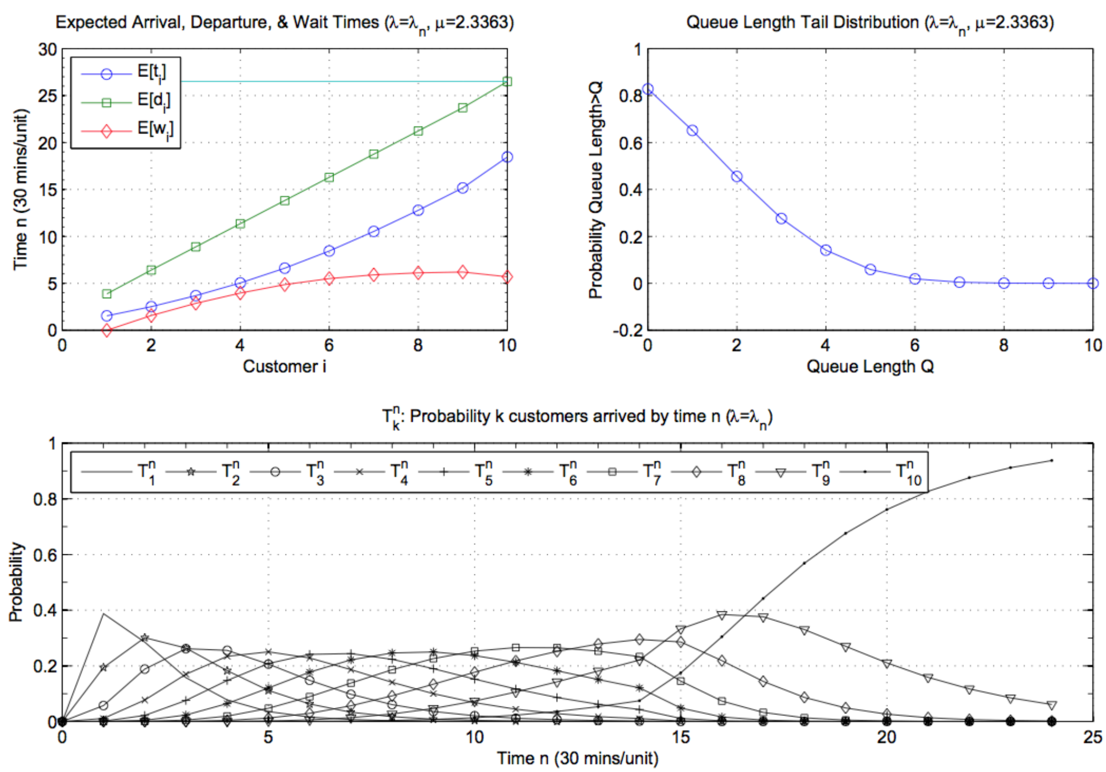


Figure 31: Numerical example 3a

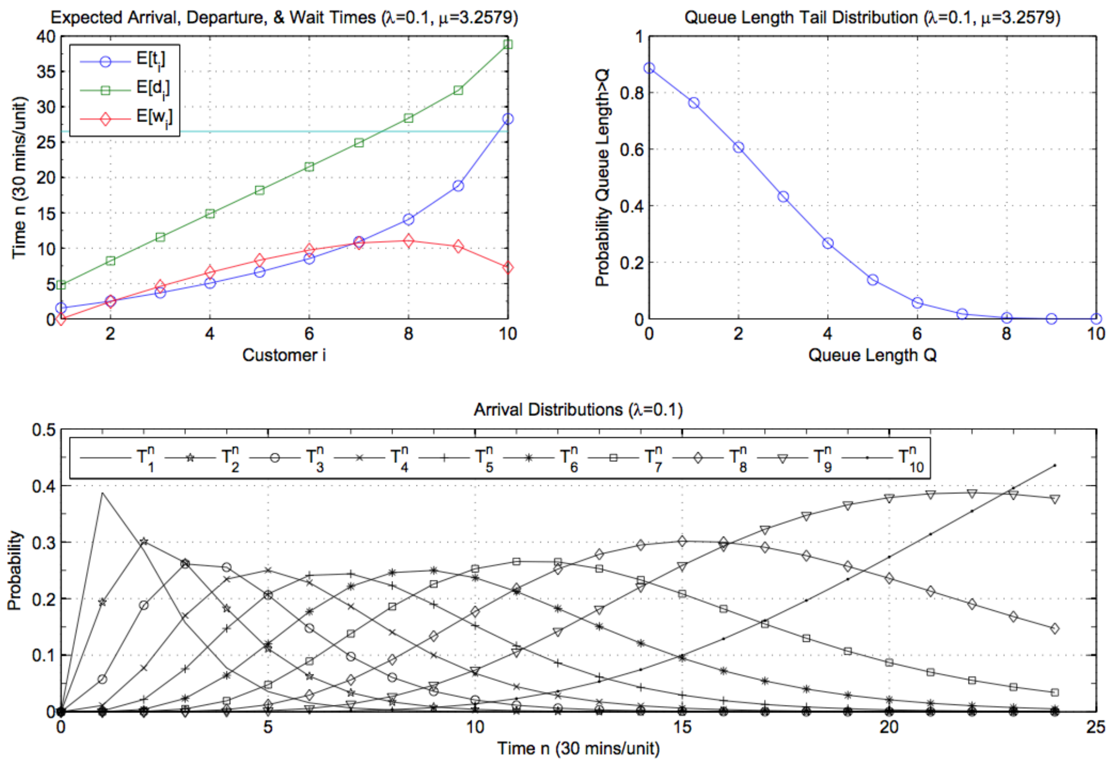


Figure 32: Numerical example 3b

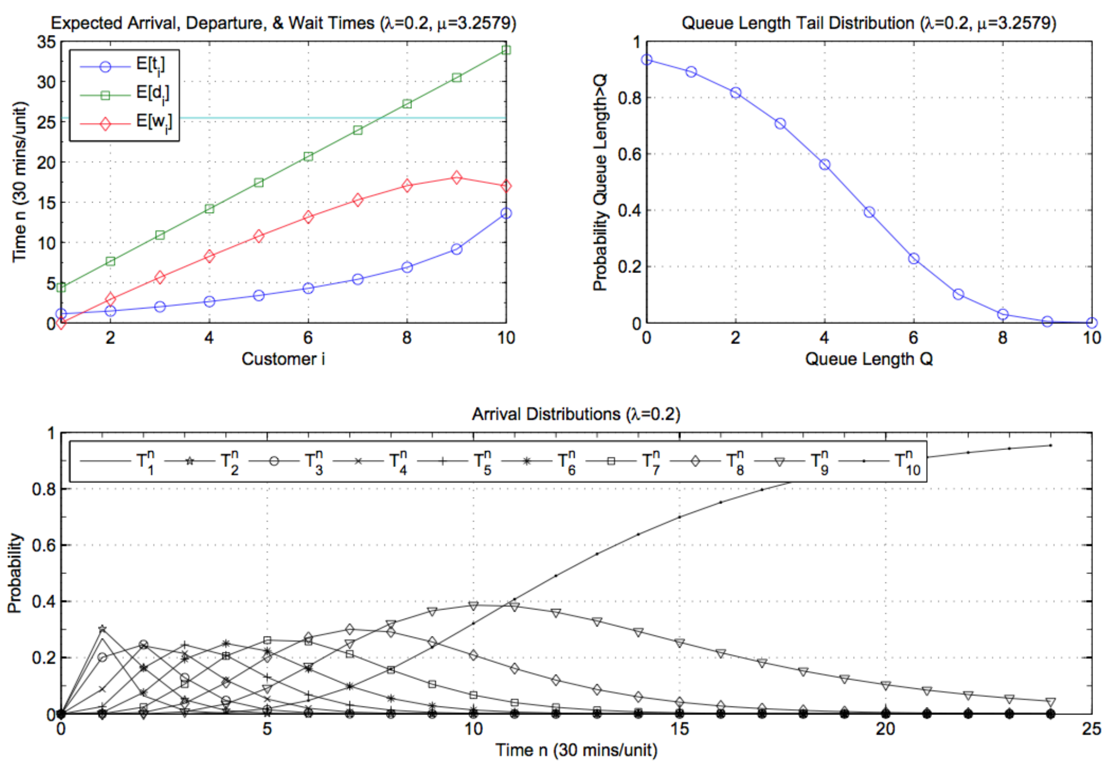


Figure 33: Numerical example 3c

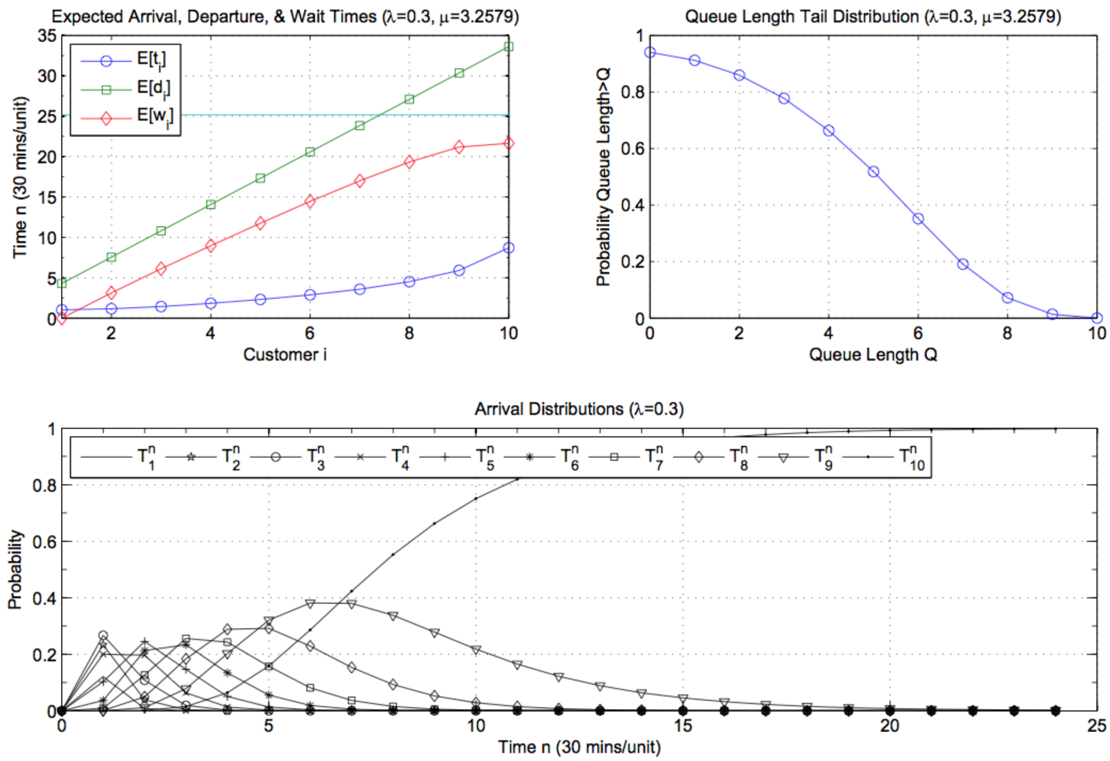
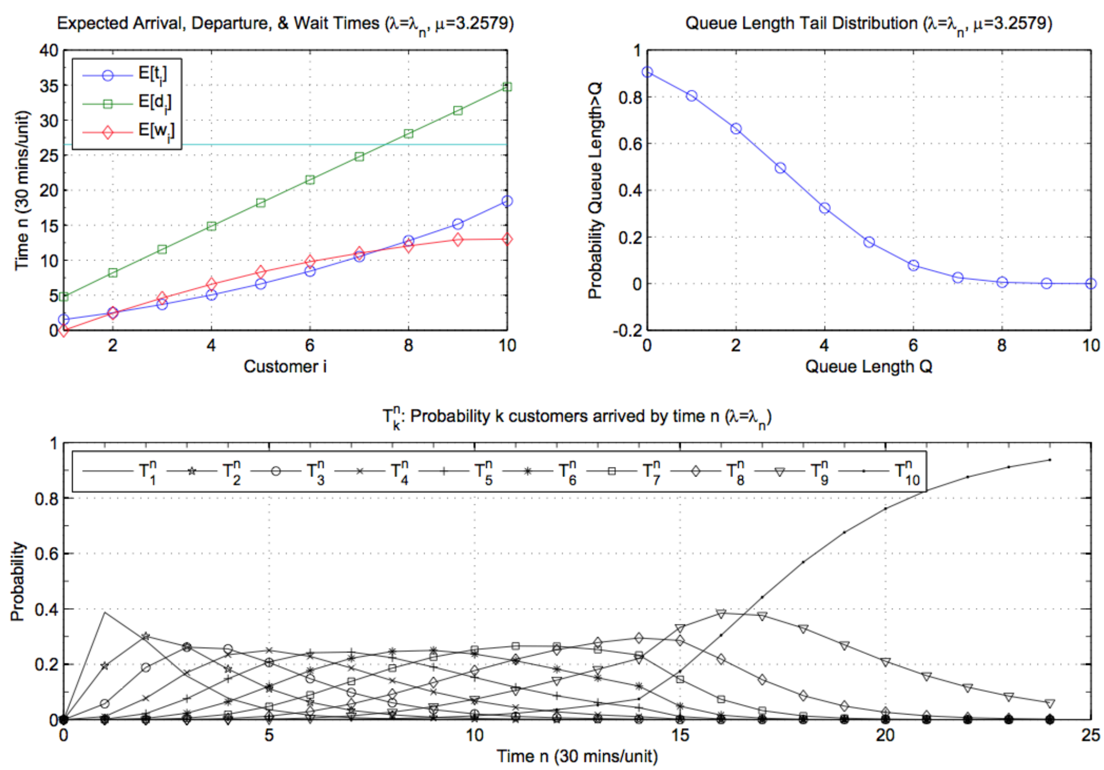


Figure 34: Numerical example 3d



CHAPTER 6

Conclusion

This thesis investigates how ABMS and QT techniques can help manage mass gathering crowds. In particular, the techniques are applied to the Hajj mass gathering, which is one of the most complex annual mass gatherings, with a focus on its challenging Tawaf ritual. The objective is to develop a Tawaf DSS, which can help better understand the Tawaf crowd dynamics and discover a set of Tawaf management decisions that lead to superior pilgrim crowd throughput, satisfaction, health, and safety. The Tawaf DSS models: (i) Tawaf crowd dynamics in the Kaaba courtyard and (ii) waiting time and queue length in the Tawaf waiting area prior to the Tawaf ritual. TawafSIM is an ABMS model, which simulates macro-level Tawaf crowd dynamics through micro-level pilgrim modeling to explore the impact of crowd characteristics, facility layout, and management preferences on emergent crowd behaviours with respect to throughput, satisfaction, health, and safety. On the other hand, TawafQT is a QT model, which uses an accurate queueing model with finite source, single service, and PH type distribution to explore the impact of pilgrim arrival rate, Tawaf throughput, and management preferences on expected pilgrim arrival, departure, and waiting times along with average queue length. This chapter concludes the thesis by discussing recommendations, limitations, contributions, future work, and closing comments.

6.1 Recommendations

The recommendations with respect to MG crowd management, DSS development, Tawaf crowd management, and Tawaf waiting area management are discussed in this subsection.

6.1.1 MG Crowd Management

Complex MGs (i.e. relatively large Mass Gathering Magnitude Scale value) like the Hajj should be studied to manage them better. Due to the Hajj's complex constraints, time-changing environment, several conflicting objectives, and large number of possible solutions, it is difficult to understand how emergent behaviour materializes, conceive the full range of outcomes that can be exhibited, gain insight into key variables and their causes, and identify decisions that lead to superior performance. Therefore, specialized research studies provide an opportunity to manage mass gathering crowd complexity.

6.1.2 DSS Development

DSS like TawafDSS should match the most appropriate modeling technique to the complex system to better understand it and identify superior performance decisions. For instance, ABMS is more applicable if the emergent behaviour in the system is influenced by individual agent behaviour. While, QT is more applicable if arrival and service distributions can adequately define the behaviour of the system. Therefore, choosing the appropriate modeling technique is essential to successful DSS development.

6.1.3 Tawaf Crowd Management

Superior Tawaf crowd management with respect to throughput, satisfaction, health, and safety requires several pragmatic steps. First, replace well-known undesirable and avoidable crowd dynamics that cause poor performance with pragmatic new Tawaf policies. The thesis recommends eliminating the disturbance to the natural flow of Tawaf crowd movement and high crowd density by placing a temporary circular barrier around the Kaaba and limiting the maximum number of pilgrims in the courtyard. Second, simulate a wide range of scenarios for the new policies to find the optimum crowd management decisions. For instance, TawafSIM simulates 42 scenarios under 12 categories to determine the set of management decisions leading to above average Tawaf crowd performance. Third, use the simulation observations to develop a Tawaf Crowd Management Guide to understand how different scenarios affect Tawaf performance. The contents of the Guide are to include subsection: 4.5.1: Emergent Crowd Behaviour Results, 4.5.2.2: Scenarios Impacting Overall Tawaf Performance, 4.5.2.3: Scenarios Impacting Individual Tawaf Metrics, and 4.5.3: Guidelines for Tawaf Crowd Management along with Figure 18: List of critical scenarios impacting each Tawaf performance metric and Figure 19: Summary of observations from each scenario. Fourth, attempt to find a subset of scenarios, which lead to superior performance. The thesis identifies the superior performance subset scenarios listed in subsection 4.5.2.1 Default Scenario.

6.1.4 Tawaf Waiting Area Management

Superior Tawaf waiting area management with respect to pilgrim group departure and waiting times along with queue length requires development of a Tawaf Waiting Area Management Guide, which describes relevant numerical example results using the TawafQT model as shown in subsection 5.5: Results. These examples suggest different recommendations for different situations. First, if the average Tawaf is 30 minutes and the objective is to have the pilgrim groups depart the waiting area as early as possible, then the pilgrim group arrival rate should be targeted to be $\lambda = 0.3$ (i.e., Example 1c) but with a trade off for the longest waiting time and queue length. Alternatively, if the objective is to minimize waiting time, then the inhomogeneous arrival rate should be targeted (i.e., Example 1d) whereas if the objective is to minimize both departure time and waiting time, then $\lambda = 0.2$ should be targeted (i.e., Example 1b). Second, if the average Tawaf is 50 minutes, then the departure time for all scenarios is approximately the same; thus the best decision is targeting the inhomogeneous arrival rate (i.e., Example 2d), which has the shortest waiting time. Finally, if the average Tawaf time is 70 minutes, then all the scenarios exceed the required maximum departure time; thus the least negative scenario is to target the inhomogeneous arrival rate (i.e., Example 3d), which has the shortest waiting time.

6.2 Limitations

The limitations with respect to MG crowd management, DSS development, Tawaf crowd management, and Tawaf waiting area management are discussed in this subsection.

6.2.1 MG Crowd Management

Only some aspects of TawafDSS can be directly reused for other MGs. TawafQT model can be applied to all MGs with a finite source and single service characteristics without any modifications to the Matlab code. However, TawafSIM Java code is too specific to the Tawaf ritual to model crowd dynamics for other MGs. Nevertheless, the throughput, satisfaction, health, and safety results from TawafSIM may serve as a useful comparison or benchmark for other MGs. As such, TawafDSS can be reused for other MGs with some restrictions.

6.2.2 DSS Development

Like most DSS, TawafDSS has decision support capability but lacks decision making capability. TawafDSS aggregates large amounts of data into useful information, then knowledge, in the form of tables and charts, which helps support decision making. For instance, "Table 13: Summary of scenario impacts on Tawaf crowd performance." provides useful knowledge, but it is insufficient to help identify the best decision to make from a large number of choices. Therefore, the TawafDSS is useful for decision support but unable to provide decision making capability.

6.2.3 Tawaf Crowd Management

TawafSIM makes several simplifications to the Tawaf crowd dynamics and uses estimates for many simulation parameters. Although TawafSIM has many features to model pilgrim characteristics, facility layout, and management preferences, TawafSIM does not model Abraham Station, pilgrim group movement, and different pilgrim body dimensions. Second, the values for most of the simulation parameters for pilgrim characteristics, facility layout, and management preferences are based on best estimates or assumptions. Therefore, although significant effort has been made to incorporate key Tawaf features along with validating and calibrating TawafSIM, it is expected the above missing features have some impact on the emergent simulation results; as well, the TawafSIM must be rerun with as many accurate simulation parameters when they are measured and made available.

6.2.4 Tawaf Waiting Area Management

TawafQT model needs to scale down the number of pilgrim groups and number of parallel servers. First, although Minh's accurate model for finite source and single service QT model is used, due to practical matrix size limits and computational inaccuracy warnings in Matlab, a maximum of 50 pilgrim groups can be executed with the model rather than the actual 1.4 million pilgrims. Second, although extending Minh's model to single-server PH type service distribution model was relatively easy and extending the single-server PH type service model to two-server PH type service model involved significant work, it is not pragmatic to extend the model to three-servers, let alone the imaginary 25,000 parallel servers used in the Tawaf with maximum 25,000 pilgrim capacity. Therefore, in order to use the TawafQT model, the service distribution has to be scaled and adjusted down to a single server with at most 50 pilgrim groups.

6.3 Contributions

The contributions with respect to MG crowd management, DSS development, Tawaf crowd management, and Tawaf waiting area management are discussed in this subsection.

6.3.1 MG Crowd Management

There are four contributions of the thesis towards MG crowd management. First, a broad definition for MGs is proposed, which suggests that MGs are common phenomena. Second, since all MGs are not of the same significance, a novel MG Magnitude Scale (MGM Scale) is proposed to rate MGs on a scale of 1 to 10 using 8 characteristics of the MG. Third, it is proposed that complex MG with a relatively high MGM Scale value should be managed after conducting a research study while less complex MGs rely on legislation, health and safety acts, and best practices to be adequately managed. Finally, it is implied through the TawafDSS that MGs not only be managed to provide required throughput, health, and safety, but also to produce satisfaction.

6.3.2 DSS Development

There are two contributions of the thesis towards DSS development. First, TawafDSS is the first research study on Tawaf crowd management (possibly Hajj crowd management), which uses a hybrid approach where the results from an ABMS model (i.e., TawafSIM) are used in a QT model (i.e., TawafQT). Second, TawafDSS is the first Tawaf crowd research, which studies both the Tawaf courtyard and also the Tawaf waiting area to provide a more complete analysis of the Tawaf ritual.

6.3.3 Tawaf Crowd Management

There are several contributions of the thesis towards Tawaf crowd management. First, TawafSIM is currently the most comprehensive simulation of the Tawaf ritual on multiple aspects. It incorporates the most features for pilgrim characteristics, facility design, and management preferences. It calculates 8 metrics for Tawaf performance, which includes one for throughput, three for satisfaction, one for health, and three for safety. It is the only Tawaf simulator to attempt to calculate satisfaction and spread of infectious disease. It conducts 42 simulation experiments in 12 categories. It generates a vast amount of Tawaf crowd observations, including emergent behaviours, tipping point behaviour, expected behaviour, and counter intuitive behaviour. It suggests a default scenario as the best scenario along with a small subset of alternative scenarios, which provide above average Tawaf performance. It generates a Tawaf Crowd Management Guide to better understand Tawaf crowd dynamics and how to pursue above average Tawaf performance under different conditions. Finally, it emphasizes simulation generated data rather than simulator generated video as a method to understand the Tawaf crowd dynamics.

Second, TawafSIM is the only Tawaf simulator that does not model the status quo Tawaf crowd dynamics with its well-known undesirable and avoidable crowd dynamics. Instead, it proposes to remove them with pragmatic temporary circular barrier, which results in significant improvement in Tawaf performance.

Third, TawafSIM provides insight into the herd immunization debate. It would seem immunization strategies which limit or decrease the total number of infected pilgrims in the Tawaf significantly decreases the chance of susceptible pilgrims getting in contact with them during the Tawaf and being affected. However, for a given number of infected pilgrims in Tawaf, having more pilgrims that are immunized in Tawaf does not create a barrier between the infecting pilgrims and the susceptible pilgrims, thus higher immunization levels does not decrease the chance of susceptible pilgrims being infected.

Fourth, TawafSIM provides a pilgrim next-step movement algorithm using a combination of macro-level trajectory through a spiral-based equation followed by micro-level refinements in movement by evaluating fitness of each Moore neighbour of the macro-level destination. This macro-micro movement algorithm allows each pilgrim to: (i) perform simple calculations to provide spiral in, maintain circle, and spiral out Tawaf movement; (ii) avoid collisions; (iii) accommodate personal congestion avoidance decisions; and (iv) provide distinct movement patterns based on pilgrim attributes and local environment conditions.

Fifth, TawafSIM is a custom built Java program, which incorporates all aspects of ABMS features decision rules, adaptive capability, perception capability, and internal models, to allow full flexibility to add Tawaf features without the limitations imposed by generic simulation platforms.

Finally, TawafSIM provides an opportunity to better understand the impact of pilgrim characteristics, Tawaf facility design, and management policies on emergent Tawaf crowd dynamics with respect to throughput, satisfaction, health, and safety.

6.3.4 Tawaf Waiting Area Management

There are four contributions of the thesis towards Tawaf waiting area management. First, TawafQT model extends Minh's discrete time, finite population with single service QT model to have PH type service distribution. Second, it extends the single-server PH type service extension model for a two-server queue with PH type service distribution. Third, TawafQT is the only study of the Tawaf waiting area using a QT model that generates a set of numerical examples in the form of a Tawaf Waiting Area Management Guide to better understand how pilgrim arrival and Tawaf throughput impact pilgrim expected arrival, departure, and waiting time along with queue length. Finally, TawafQT is not only applicable to the Tawaf and other Hajj related queueing systems, but also to any other queueing system that has finite population and single service characteristics.

6.4 Future work

The future work with respect to MG crowd management, DSS development, Tawaf crowd management, and Tawaf waiting area management are discussed in this subsection.

6.4.1 MG Crowd Management

Compute the MGM Scale for as many historical MGs as possible to determine how well the MGM Scale is able to measure the potential fatal impact of MGs. As well, determine at what threshold should MGs be considered complex and warrant an in-depth research study to determine how best to manage them.

6.4.2 DSS Development

Since the TawafDSS is useful for decision support but unable to provide decision making capability, it would be useful to extend the capability of the DSS to develop an autonomous system to find and recommend optimum Tawaf crowd management decisions. In particular, a real-time Tawaf crowd tracking system with a component to predict the future state of the Tawaf crowd along with optimization techniques could be used to autonomously find the set of best decisions for above average performance.

6.4.3 Tawaf Crowd Management

It is essential to generate a common comprehensive Tawaf crowd dataset, which can be used to calibrate and validate all existing and future Tawaf crowd simulator. This would include collecting anonymous data on pilgrim characteristics and experience through pre- and post-Hajj surveys, pilgrim Tawaf movement telemetry data, extracting non-movement Tawaf dynamics data from video footage, and infectious disease spreading data.

TawafSIM can be enhanced to model Abraham Station, pilgrim group movement, and different pilgrim body dimensions to see the difference between the original and enhanced model results. Furthermore, TawafSIM can be extended to model the Tawaf crowd dynamics on the non-courtyard Tawaf areas (i.e., second floor and roof) to see how the results differ in the different Tawaf areas.

6.4.4 Tawaf Waiting Area Management

The current conditional probability for $g_{v,k}^{n}$ using λ can not fully accommodate a custom user defined pilgrim arrival distribution based on pilgrim preference, scheduling plan, or transportation system constraints. Therefore, $g_{v,k}^{n}$ can be manually set to match the custom user defined arrival distribution.

TawafQT can be used to analyze other Hajj related queueing systems to compare the results between the TawafQT finite source, single service QT model and the existing modeling technique.

6.5 Closing comments

In summary, TawafSIM is an example of a Hajj ABMS, which allows Hajj authorities to determine the impact of pilgrim characteristics, facility layout, and management preferences on crowd performance with respect to throughput, satisfaction, health, and safety. As well, TawafQT is an example of a Hajj QT model for finite population with single service, which allows Hajj authorities to better predict pilgrim arrival, departure, and waiting times along with pilgrim queue length for different combination of pilgrim arrival and service times at Hajj sites.

In closing, this thesis provides the state-of-the-art, specialized, and custom-built Hajj crowd management decision support system using ABMS and QT to help Hajj authorities discover superior Hajj performance decisions.

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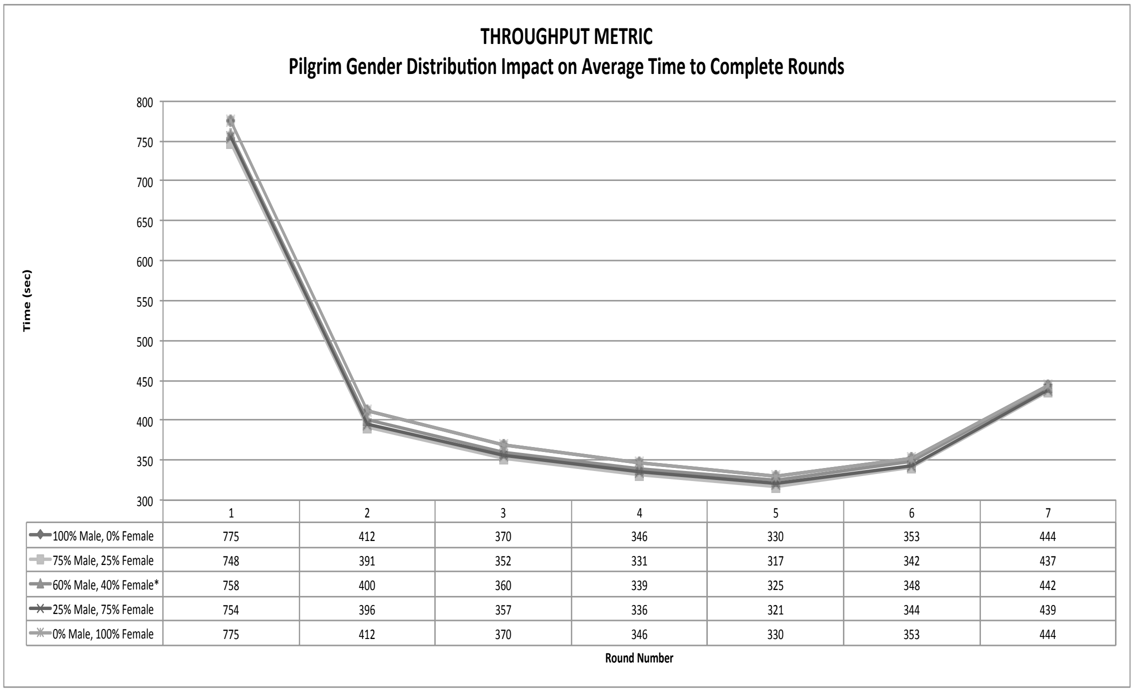
Appendix A:

TawafSIM Throughput Metric Figures

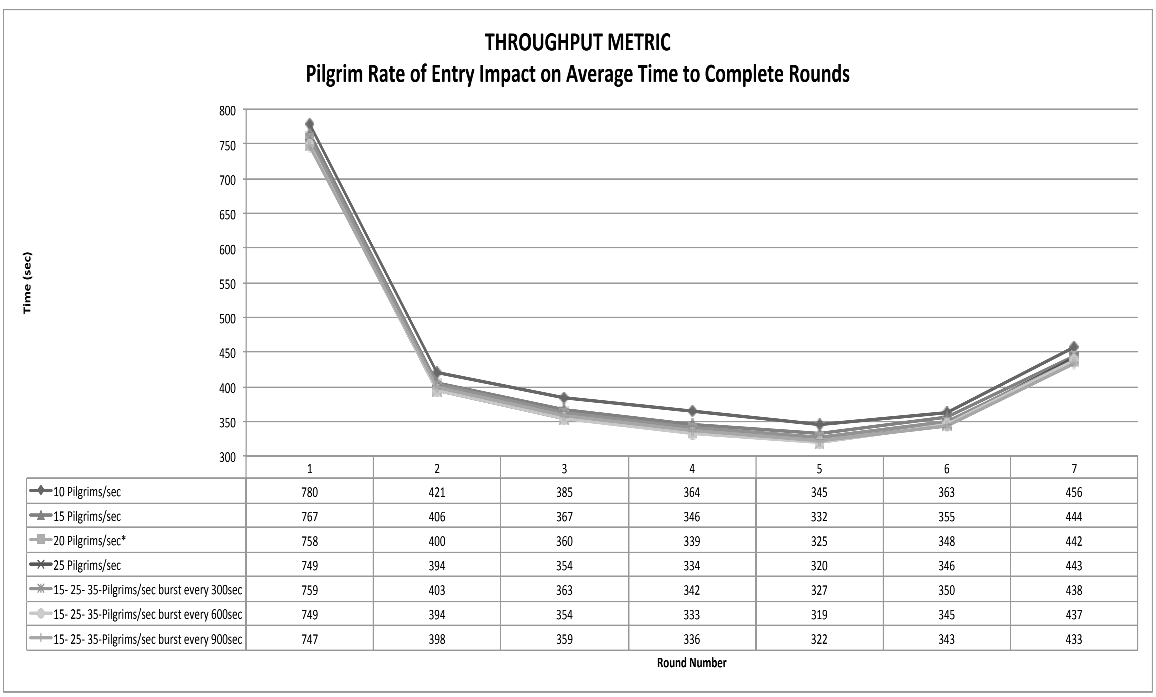
Figure 35: Gender impact on time to complete rounds.



	1	2	3	4	5	6	7
100% Male, 0% Female	775	412	370	346	330	353	444
75% Male, 25% Female	748	391	352	331	317	342	437
60% Male, 40% Female*	758	400	360	339	325	348	442
25% Male, 75% Female	754	396	357	336	321	344	439
0% Male, 100% Female	775	412	370	346	330	353	444

* Default scenario 1 along with scenarios 2 to 5.

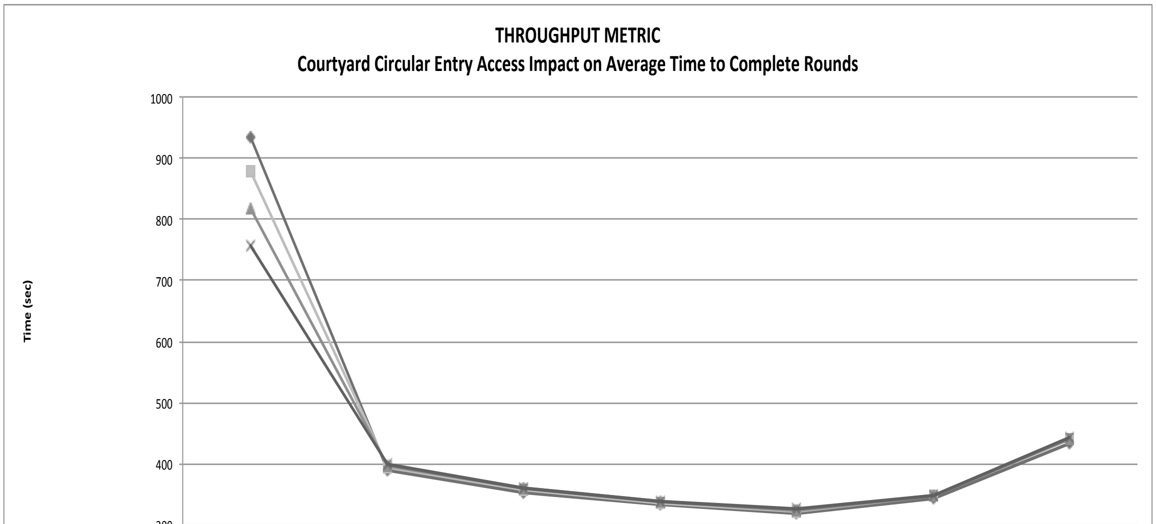
Figure 36: Rate of entry impact on time to complete rounds.



	1	2	3	4	5	6	7
10 Pilgrims/sec	780	421	385	364	345	363	456
15 Pilgrims/sec	767	406	367	346	332	355	444
20 Pilgrims/sec*	758	400	360	339	325	348	442
25 Pilgrims/sec	749	394	354	334	320	346	443
15- 25- 35-Pilgrims/sec burst every 300sec	759	403	363	342	327	350	438
15- 25- 35-Pilgrims/sec burst every 600sec	749	394	354	333	319	345	437
15- 25- 35-Pilgrims/sec burst every 900sec	747	398	359	336	322	343	433

* Default scenario 1 along with scenarios 6 to 11.

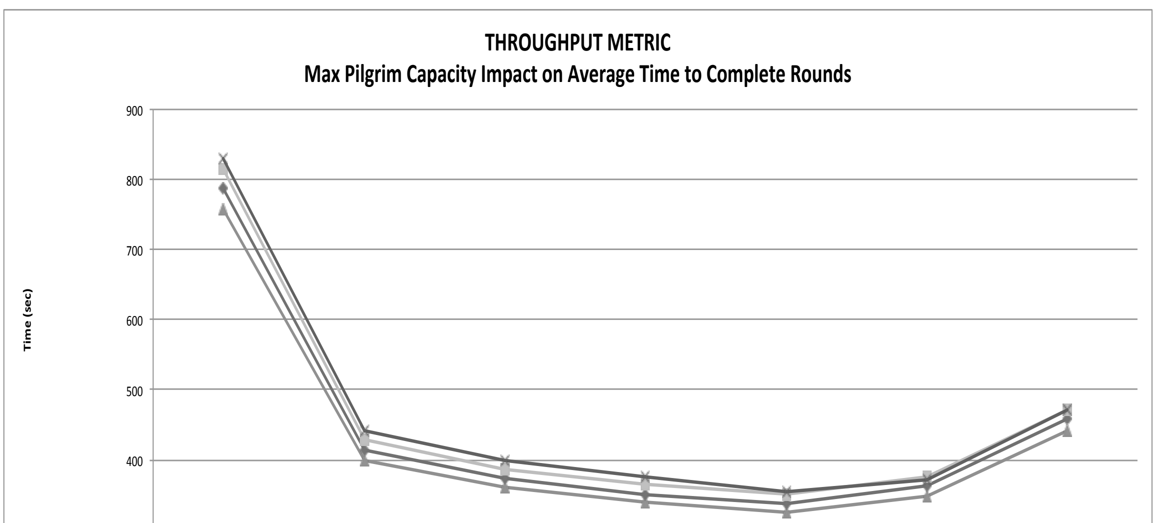
Figure 37: Courtyard access impact on time to complete rounds.



	1	2	3	4	5	6	7
25% Circular Entry Access	936	389	353	332	318	343	434
50% Circular Entry Access	879	394	357	336	322	347	441
75% Circular Entry Access	819	397	359	337	323	348	441
100% Circular Entry Access*	758	400	360	339	325	348	442

* Default scenario 1 along with scenarios 12 to 14.

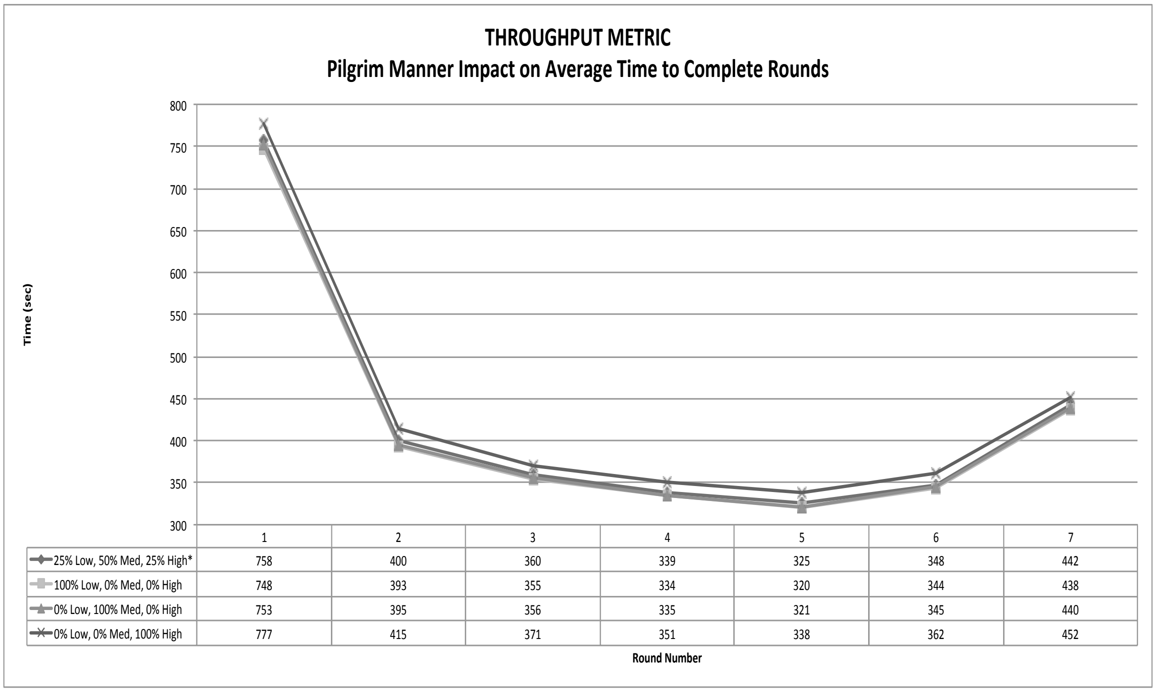
Figure 38: Capacity impact on time to complete rounds.



	1	2	3	4	5	6	7
25,000 Max Pilgrims*	758	400	360	339	325	348	442
30,000 Max Pilgrims	787	414	373	351	337	363	458
35,000 Max Pilgrims	815	429	387	364	351	375	472
40,000 Max Pilgrims	831	442	398	375	354	371	471

* Default scenario 1 along with scenarios 15 to 17.

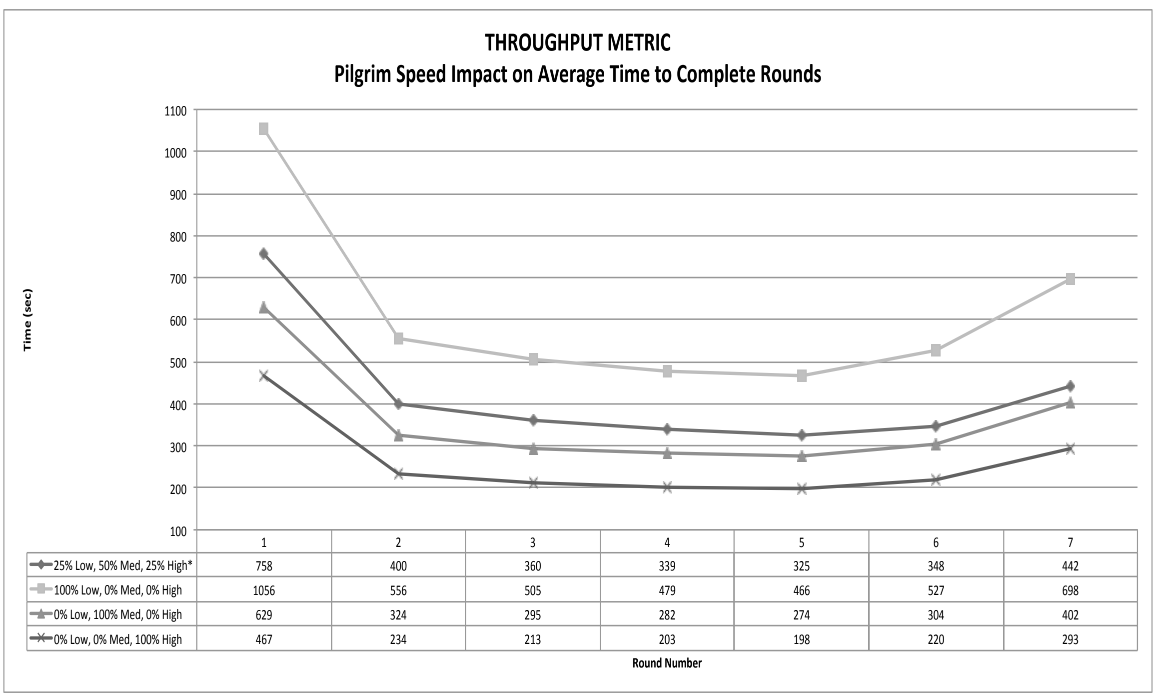
Figure 39: Manner impact on time to complete rounds.



	1	2	3	4	5	6	7
25% Low, 50% Med, 25% High*	758	400	360	339	325	348	442
100% Low, 0% Med, 0% High	748	393	355	334	320	344	438
0% Low, 100% Med, 0% High	753	395	356	335	321	345	440
0% Low, 0% Med, 100% High	777	415	371	351	338	362	452

* Default scenario 1 along with scenarios 18 to 20.

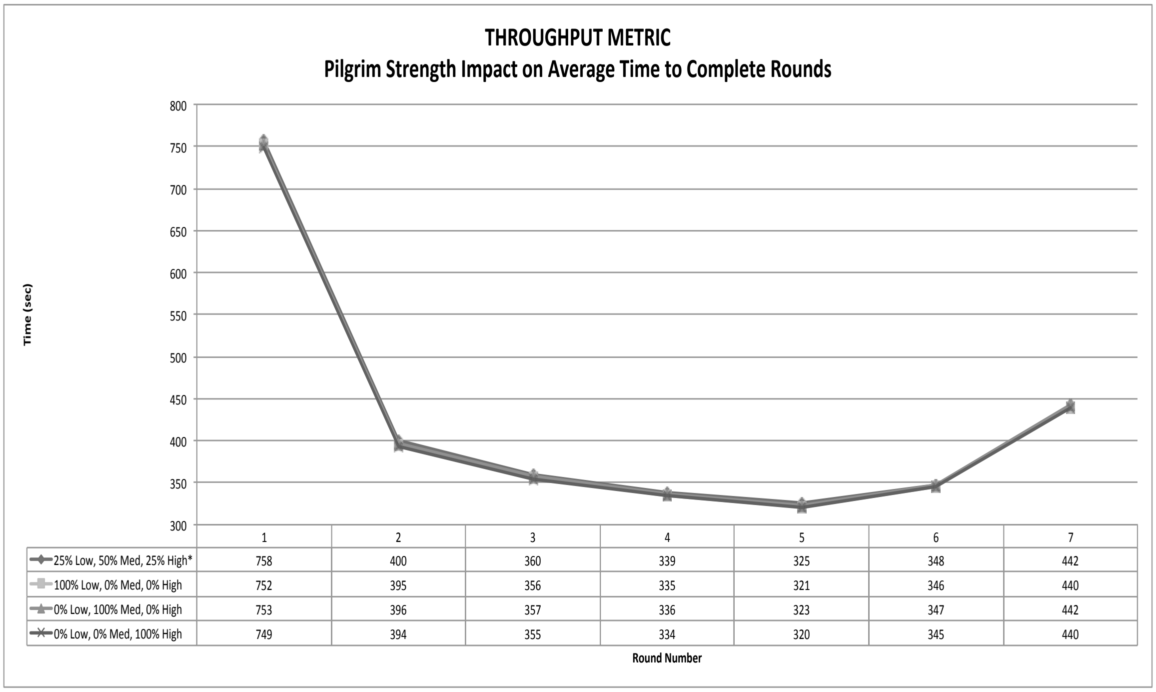
Figure 40: Speed impact on time to complete rounds.



	1	2	3	4	5	6	7
25% Low, 50% Med, 25% High*	758	400	360	339	325	348	442
100% Low, 0% Med, 0% High	1056	556	505	479	466	527	698
0% Low, 100% Med, 0% High	629	324	295	282	274	304	402
0% Low, 0% Med, 100% High	467	234	213	203	198	220	293

* Default scenario 1 along with scenarios 21 to 23.

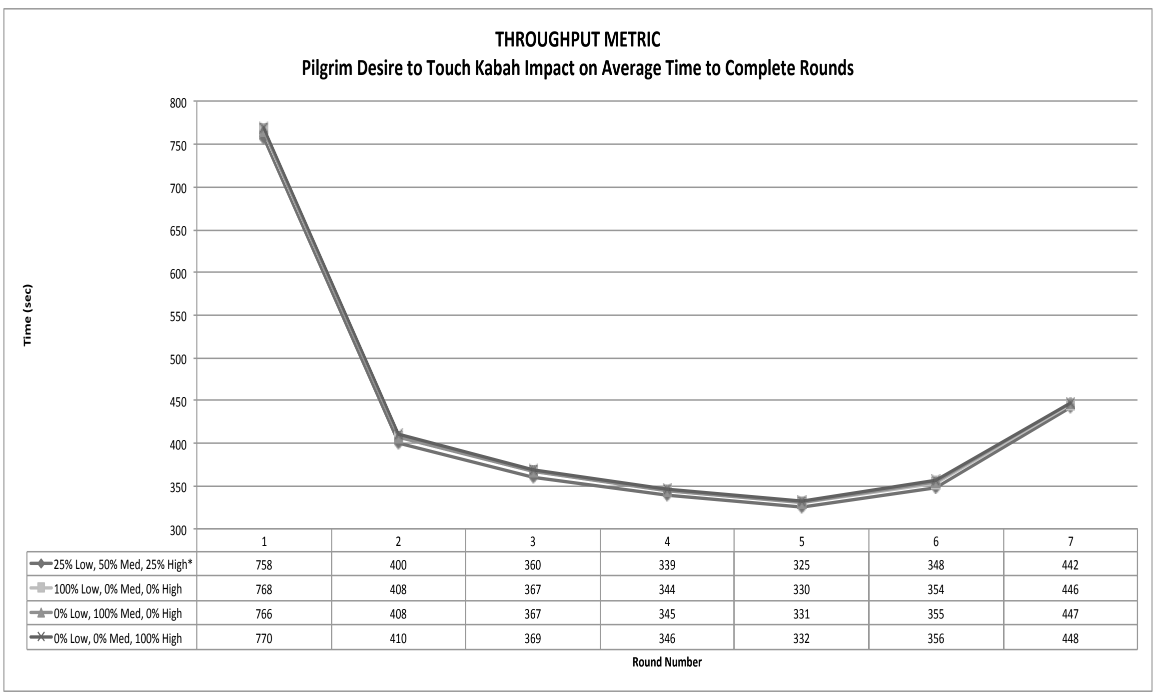
Figure 41: Strength impact on time to complete rounds.



	1	2	3	4	5	6	7
25% Low, 50% Med, 25% High*	758	400	360	339	325	348	442
100% Low, 0% Med, 0% High	752	395	356	335	321	346	440
0% Low, 100% Med, 0% High	753	396	357	336	323	347	442
0% Low, 0% Med, 100% High	749	394	355	334	320	345	440

* Default scenario 1 along with scenarios 24 to 26.

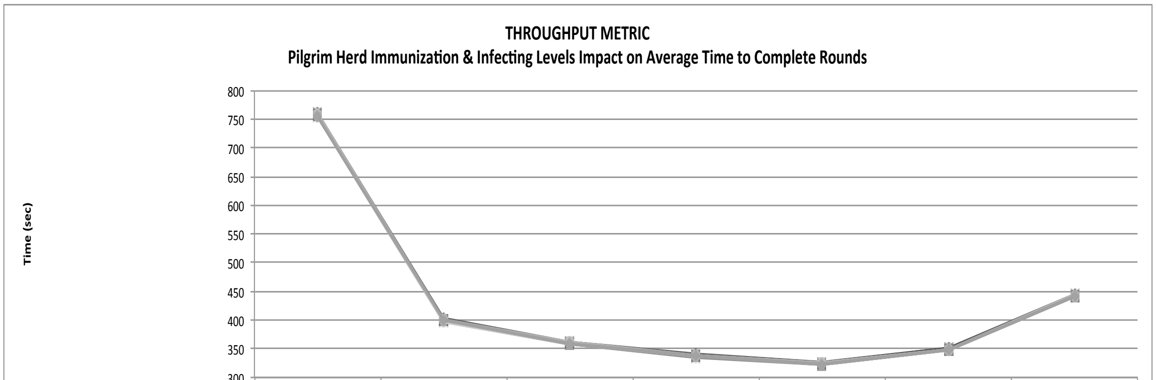
Figure 42: Desire to touch Kaaba impact on time to complete rounds.



	1	2	3	4	5	6	7
25% Low, 50% Med, 25% High*	758	400	360	339	325	348	442
100% Low, 0% Med, 0% High	768	408	367	344	330	354	446
0% Low, 100% Med, 0% High	766	408	367	345	331	355	447
0% Low, 0% Med, 100% High	770	410	369	346	332	356	448

* Default scenario 1 along with scenarios 27 to 29.

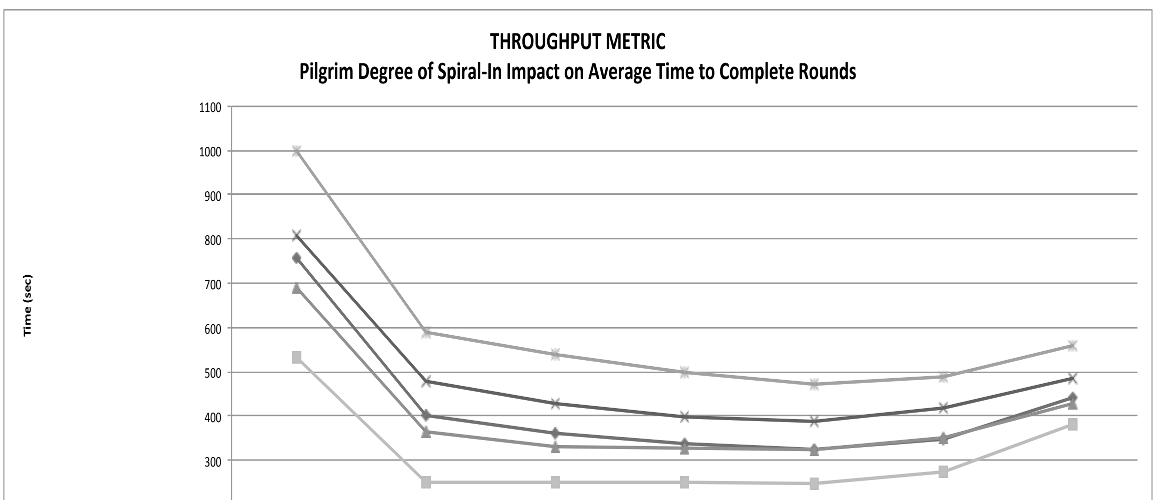
Figure 43: Health impact on time to complete rounds.



	1	2	3	4	5	6	7
20% Immunized, 70% Normal, 10% Infecting	761	402	362	340	326	350	444
20% Immunized, 60% Normal, 20% Infecting	757	399	359	338	323	349	442
20% Immunized, 50% Normal, 30 Infecting*	758	400	360	339	325	348	442
20% Immunized, 40% Normal, 40% Infecting	759	400	361	339	325	350	443
20% Immunized, 30% Normal, 50% Infecting	755	397	358	336	323	348	442
0% Immunized, 70% Normal, 30% Infecting	758	399	360	338	324	349	442
10% Immunized, 60% Normal, 30% Infecting	755	398	358	337	323	347	441
30% Immunized, 40% Normal, 30% Infecting	757	398	359	337	324	349	443
40% Immunized, 30% Normal, 30% Infecting	760	401	360	339	325	349	443
50% Immunized, 20% Normal, 30% Infecting	756	399	358	337	323	348	442

* Default scenario 1 along with scenarios 30 to 38.

Figure 44: Degree of spiralling impact on time to complete rounds.



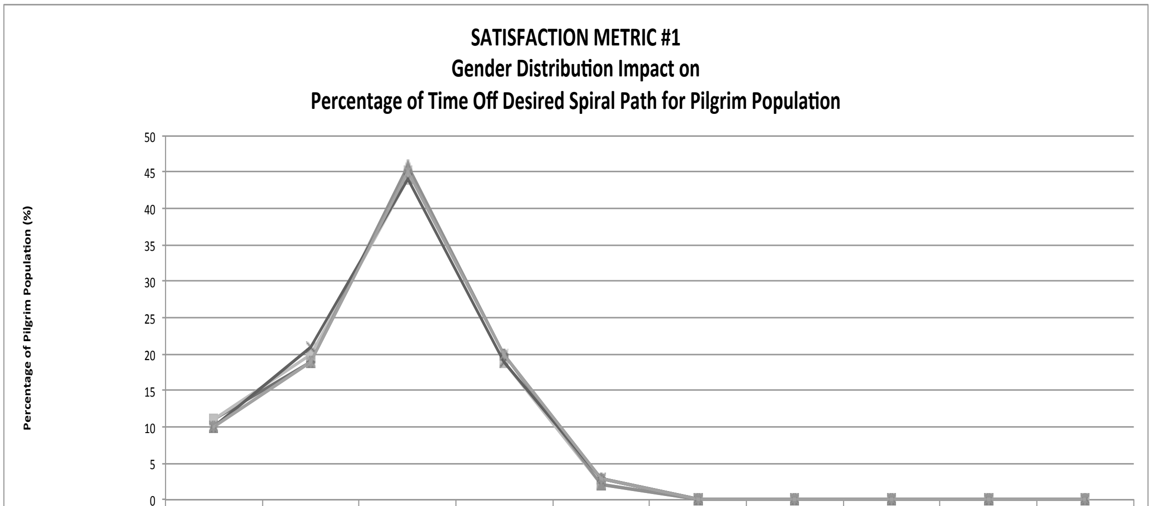
	1	2	3	4	5	6	7
25% n=1, 25% n=2, 25% n=3, 25% n=4*	758	400	360	339	325	348	442
100% n=1, 0% n=2, 0% n=3, 0% n=4	534	252	252	251	248	274	380
0% n=1, 100% n=2, 0% n=3, 0% n=4	690	365	331	327	323	351	429
0% n=1, 0% n=2, 100% n=3, 0% n=4	806	478	429	397	388	417	486
0% n=1, 0% n=2, 0% n=3, 100% n=4	1000	590	539	499	471	489	560

* Default scenario 1 along with scenarios 39 to 42.

Appendix B:

TawafSIM Satisfaction Metric #1 Figures

Figure 45: Gender impact on time off desired spiral path.

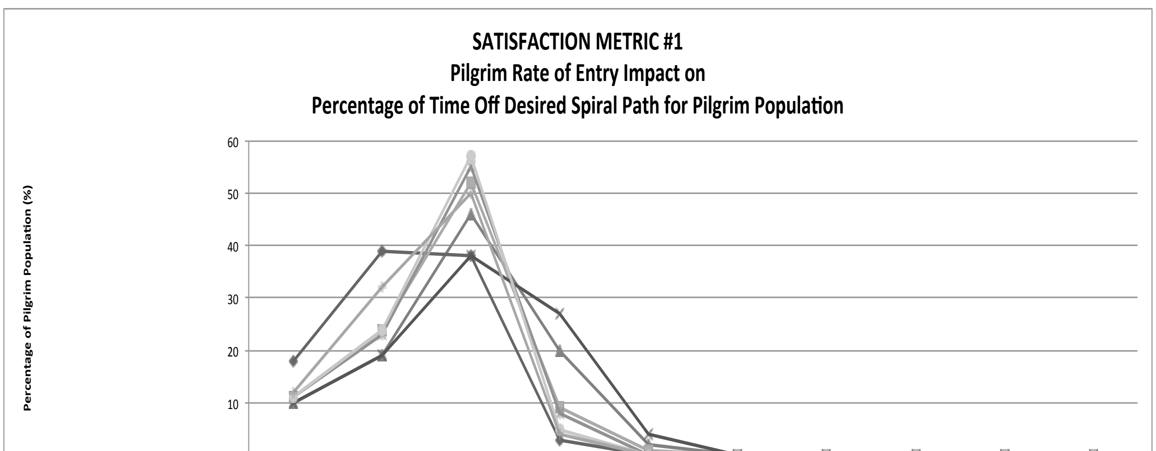


	10	20	30	40	50	60	70	80	90	100
100% Male, 0% Female	11	19	45	20	3	0	0	0	0	
75% Male, 25% Female	11	20	44	19	2	0	0	0	0	0
60% Male, 40% Female*	10	19	46	20	2	0	0	0	0	0
25% Male, 75% Female	10	21	44	19	3	0	0	0	0	0
0% Male, 100% Female	10	19	45	20	3	0	0	0	0	0

Percentage of Time Off Spiral Path (%)

* Default scenario 1 along with scenarios 2 to 5.

Figure 46: Rate of entry impact on time off desired spiral path.

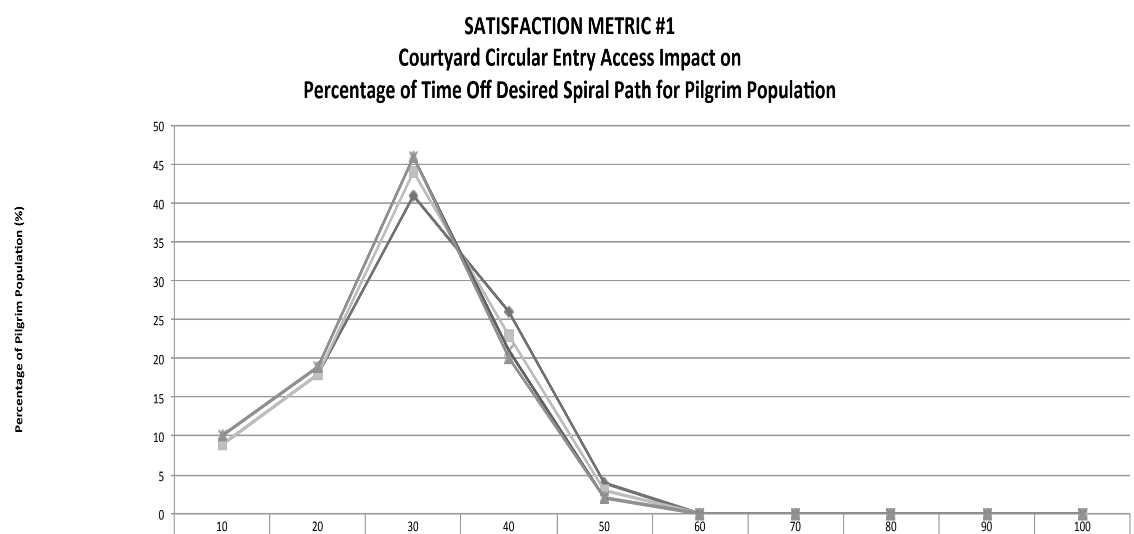


	10	20	30	40	50	60	70	80	90	100
20 Pilgrims/sec*	10	19	46	20	2	0	0	0	0	0
10 Pilgrims/sec	18	39	38	3	0	0	0	0	0	
15 Pilgrims/sec	11	24	52	9	1	0	0	0	0	0
25 Pilgrims/sec	10	19	38	27	4	0	0	0	0	0
15- 25- 35-Pilgrims/sec burst every 300 sec	11	23	55	8	0	0	0	0	0	0
15- 25- 35-Pilgrims/sec burst every 600 sec	11	24	57	5	0	0	0	0	0	0
15- 25- 35-Pilgrims/sec burst every 900 sec	12	32	50	4	0	0	0	0	0	0

Percentage of Time Off Spiral Path (%)

* Default scenario 1 along with scenarios 6 to 11.

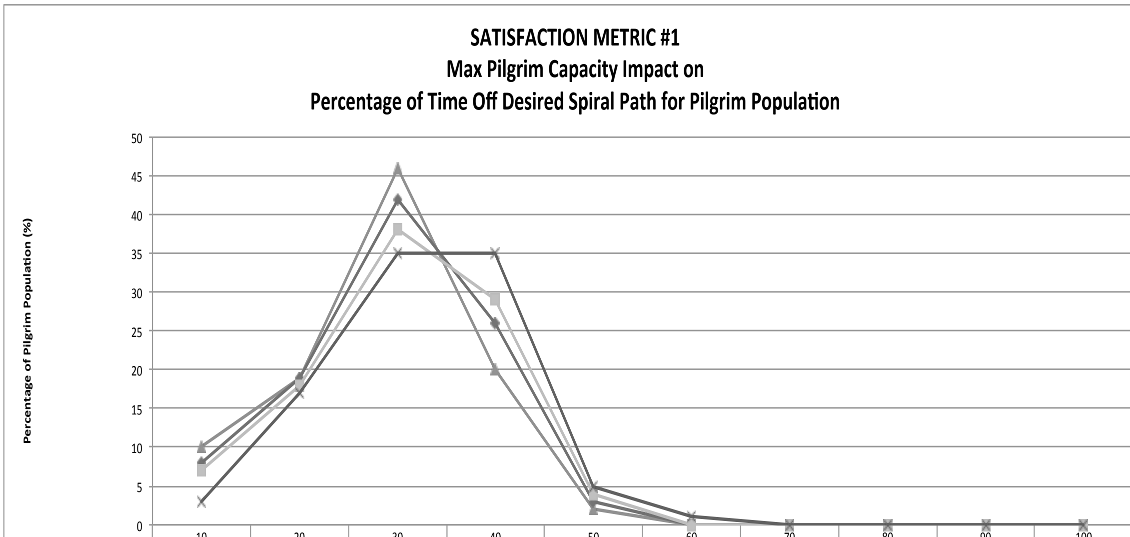
Figure 47: Courtyard access impact on time off desired spiral path.



	10	20	30	40	50	60	70	80	90	100
25% Circular Entry Access	9	18	41	26	4	0	0	0	0	
50% Circular Entry Access	9	18	44	23	3	0	0	0	0	0
75% Circular Entry Access	10	19	46	21	2	0	0	0	0	0
100% Circular Entry Access*	10	19	46	20	2	0	0	0	0	0

* Default scenario 1 along with scenarios 12 to 14.

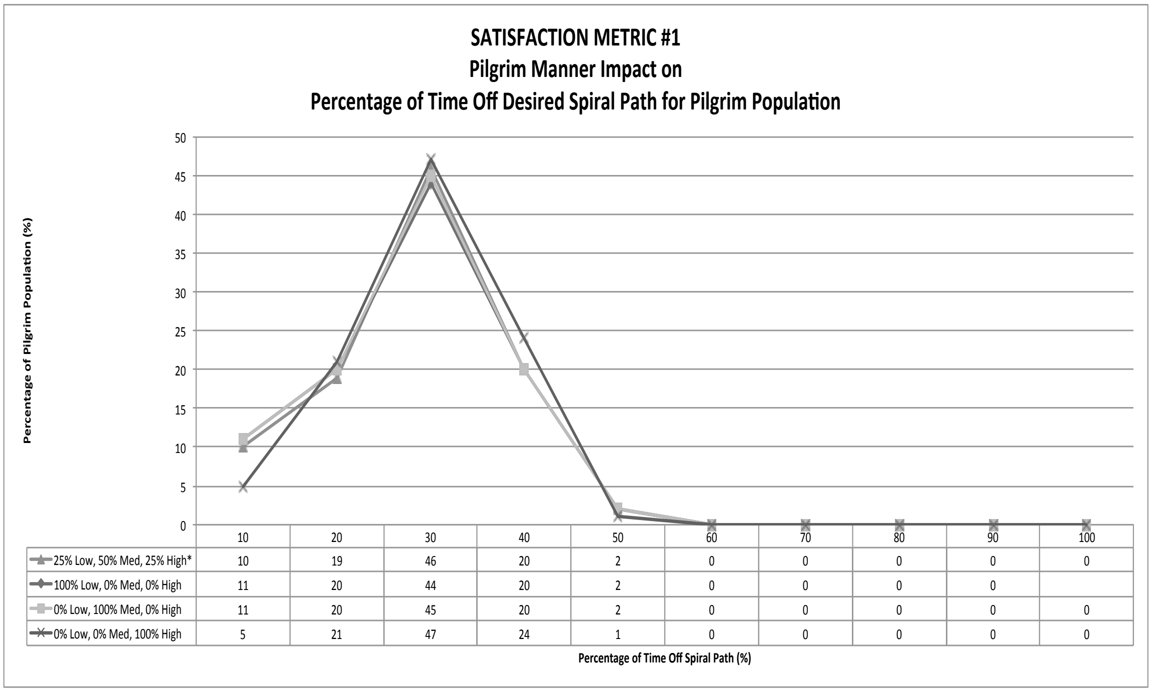
Figure 48: Capacity impact on time off desired spiral path.



	10	20	30	40	50	60	70	80	90	100
25,000 Max Pilgrims*	10	19	46	20	2	0	0	0	0	0
30,000 Max Pilgrims	8	19	42	26	3	0	0	0	0	
35,000 Max Pilgrims	7	18	38	29	4	0	0	0	0	0
40,000 Max Pilgrims	3	17	35	35	5	1	0	0	0	0

* Default scenario 1 along with scenarios 15 to 17.

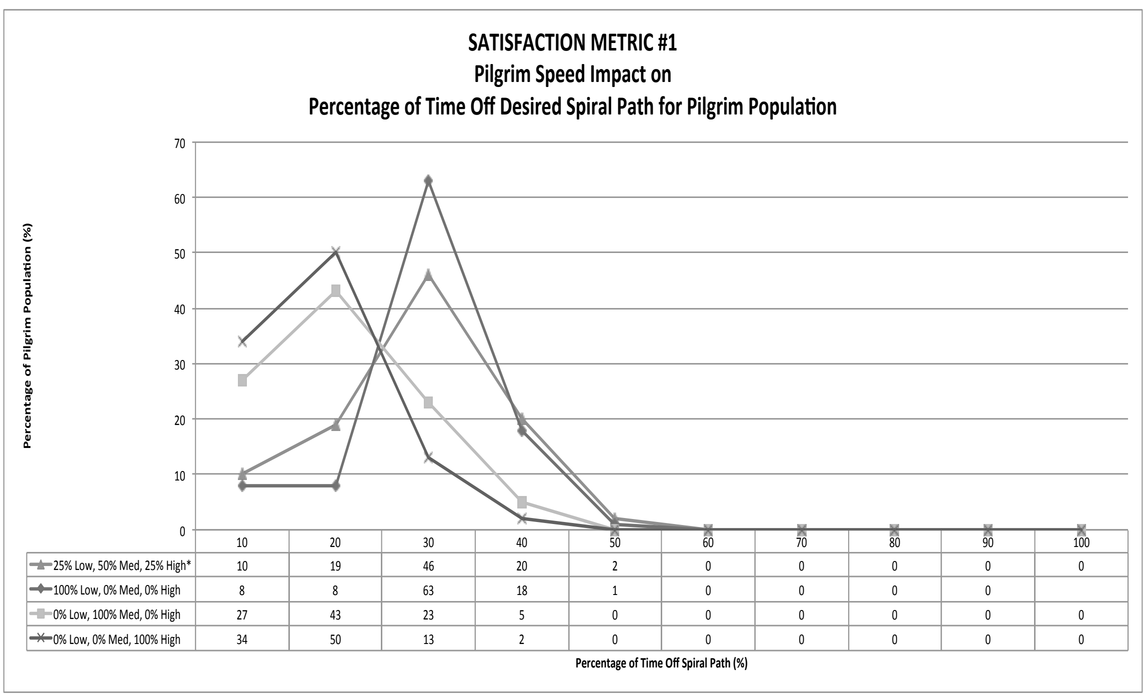
Figure 49: Manner impact on time off desired spiral path.



	10	20	30	40	50	60	70	80	90	100
25% Low, 50% Med, 25% High*	10	19	46	20	2	0	0	0	0	0
100% Low, 0% Med, 0% High	11	20	44	20	2	0	0	0	0	
0% Low, 100% Med, 0% High	11	20	45	20	2	0	0	0	0	0
0% Low, 0% Med, 100% High	5	21	47	24	1	0	0	0	0	0

* Default scenario 1 along with scenarios 18 to 20.

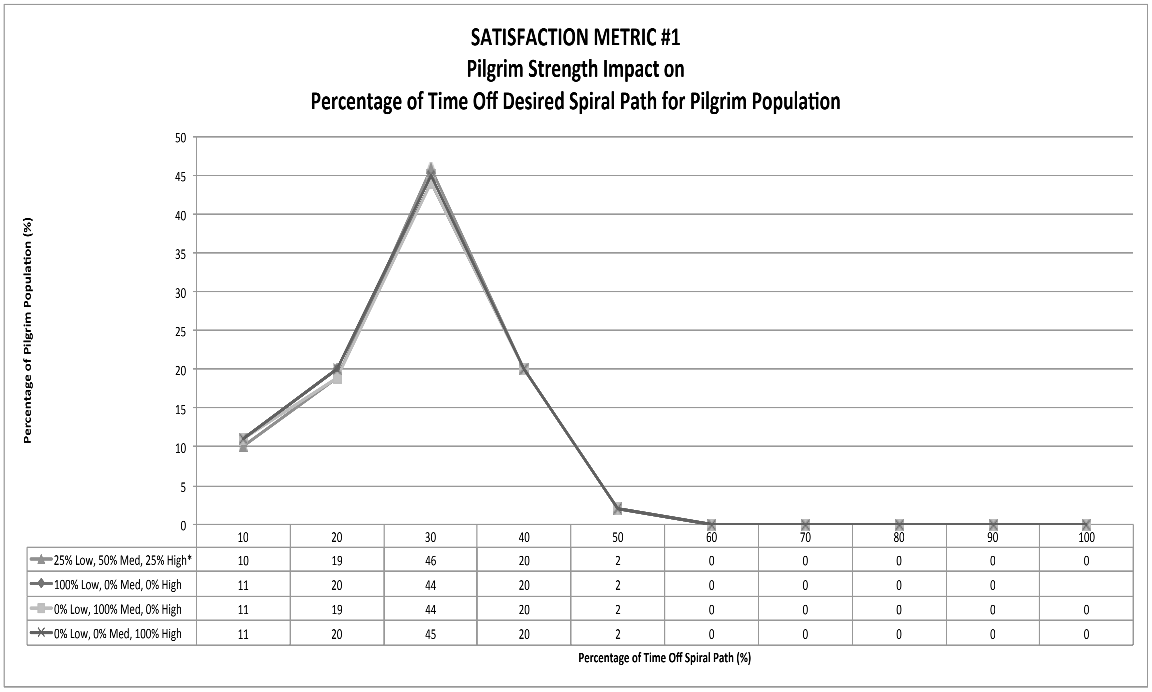
Figure 50: Speed impact on time off desired spiral path.



	10	20	30	40	50	60	70	80	90	100
25% Low, 50% Med, 25% High*	10	19	46	20	2	0	0	0	0	0
100% Low, 0% Med, 0% High	8	8	63	18	1	0	0	0	0	
0% Low, 100% Med, 0% High	27	43	23	5	0	0	0	0	0	0
0% Low, 0% Med, 100% High	34	50	13	2	0	0	0	0	0	0

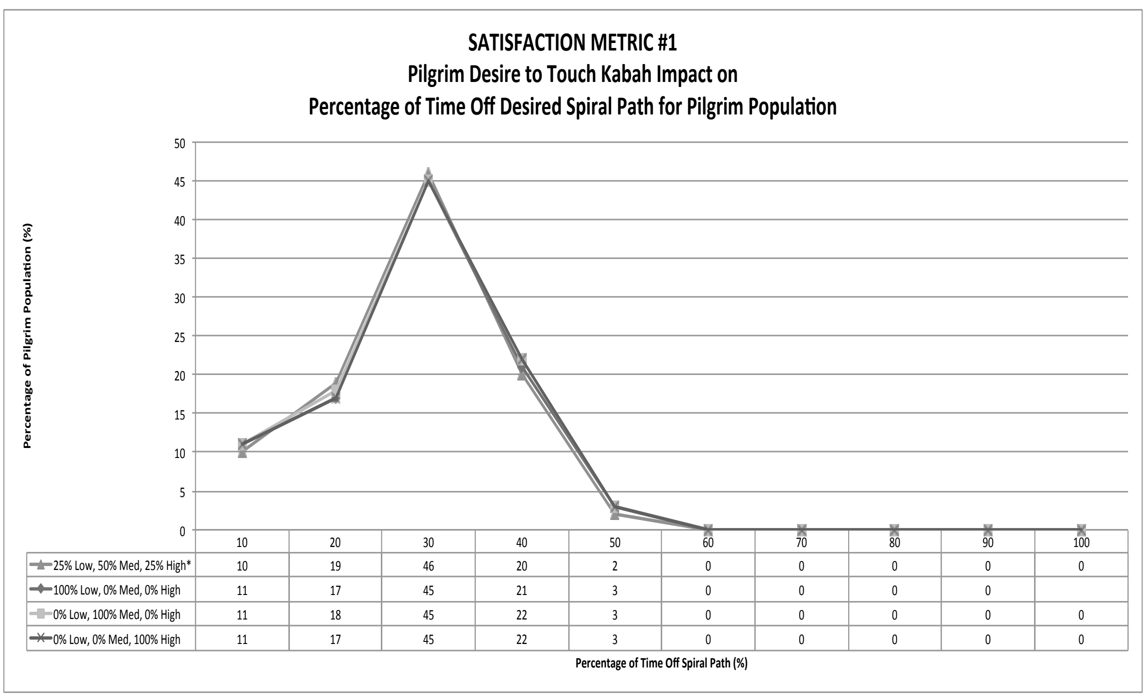
* Default scenario 1 along with scenarios 21 to 23.

Figure 51: Strength impact on time off desired spiral path.



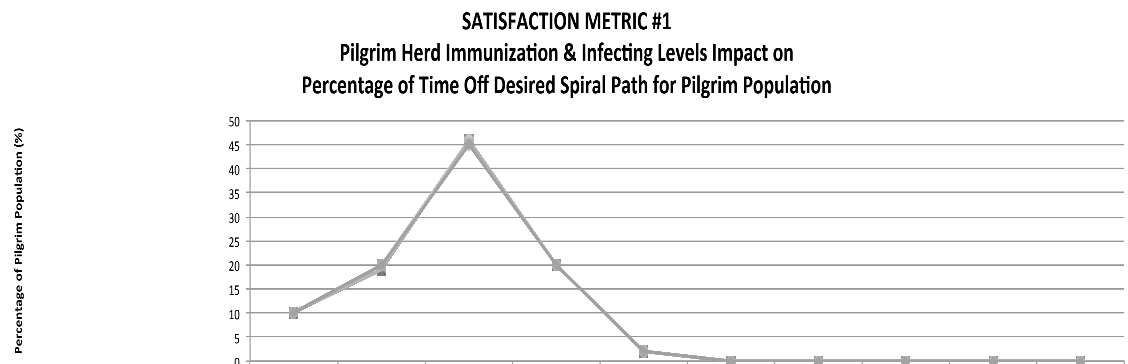
* Default scenario 1 along with scenarios 24 to 26.

Figure 52: Desire to touch Kaaba impact on time off desired spiral path.



* Default scenario 1 along with scenarios 27 to 29.

Figure 53: Health impact on time off desired spiral path.

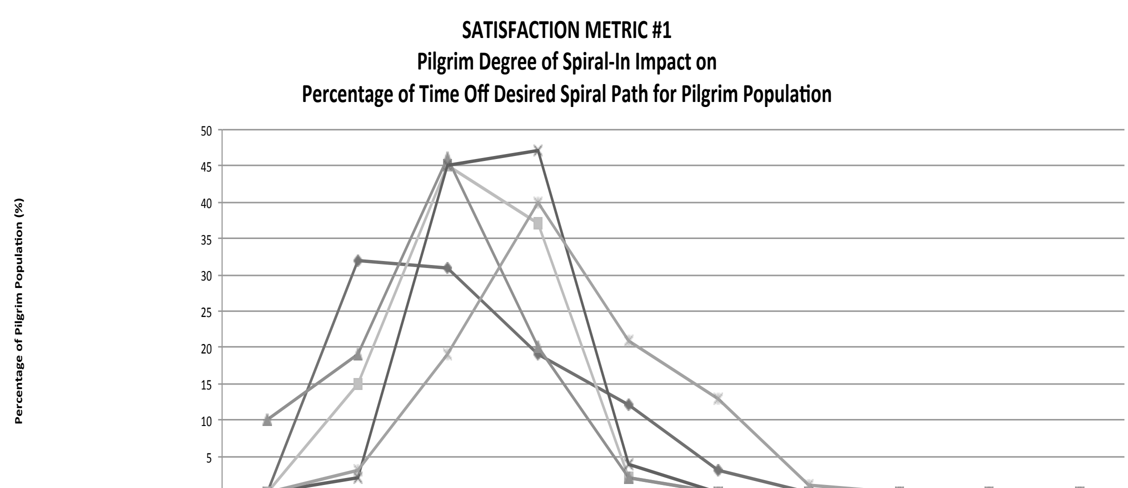


	10	20	30	40	50	60	70	80	90	100
20% Immunized, 70% Normal, 10% Infecting	10	19	46	20	2	0	0	0	0	
20% Immunized, 60% Normal, 20% Infecting	10	20	46	20	2	0	0	0	0	0
20% Immunized, 50% Normal, 30% Infecting*	10	19	46	20	2	0	0	0	0	0
20% Immunized, 40% Normal, 40% Infecting	10	19	46	20	2	0	0	0	0	0
20% Immunized, 30% Normal, 50% Infecting	10	20	46	20	2	0	0	0	0	0
0% Immunized, 70% Normal, 30% Infecting	10	20	46	20	2	0	0	0	0	0
10% Immunized, 60% Normal, 30% Infecting	10	20	45	20	2	0	0	0	0	0
30% Immunized, 40% Normal, 30% Infecting	10	20	46	20	2	0	0	0	0	0
40% Immunized, 30% Normal, 30% Infecting	10	19	46	20	2	0	0	0	0	0
50% Immunized, 20% Normal, 30% Infecting	10	20	45	20	2	0	0	0	0	0

Percentage of Time Off Spiral Path (%)

* Default scenario 1 along with scenarios 30 to 38.

Figure 54: Degree of spiralling impact on time off desired spiral path.



	10	20	30	40	50	60	70	80	90	100
100% n=1, 0% n=2, 0% n=3, 0% n=4	0	32	31	19	12	3	0	0	0	
0% n=1, 100% n=2, 0% n=3, 0% n=4	0	15	45	37	2	0	0	0	0	0
25% n=1, 25% n=2, 25% n=3, 25% n=4*	10	19	46	20	2	0	0	0	0	0
0% n=1, 0% n=2, 100% n=3, 0% n=4	0	2	45	47	4	0	0	0	0	0
0% n=1, 0% n=2, 0% n=3, 100% n=4	0	3	19	40	21	13	1	0	0	0

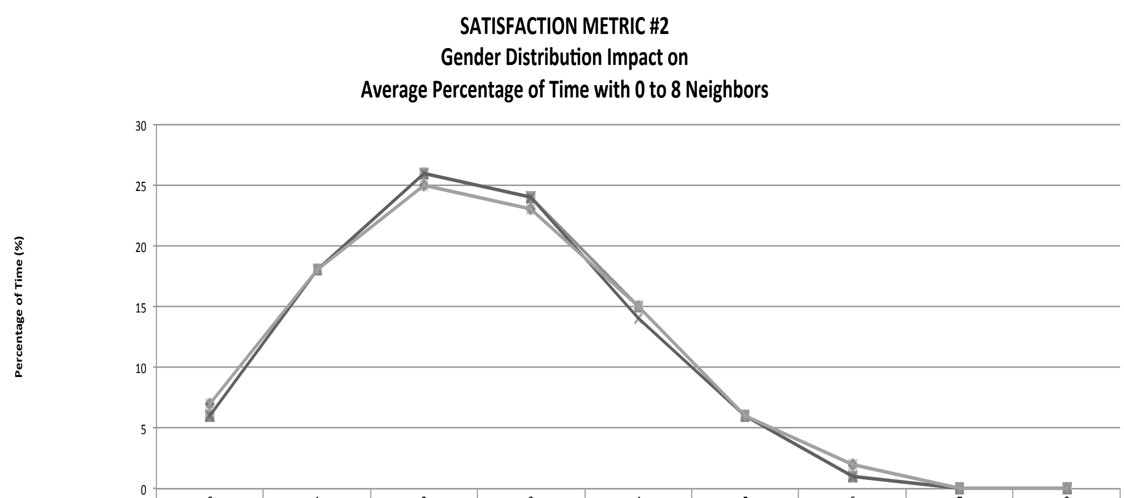
Percentage of Time Off Spiral Path (%)

* Default scenario 1 along with scenarios 39 to 42.

Appendix C:

TawafSIM Satisfaction Metric #2 Figures

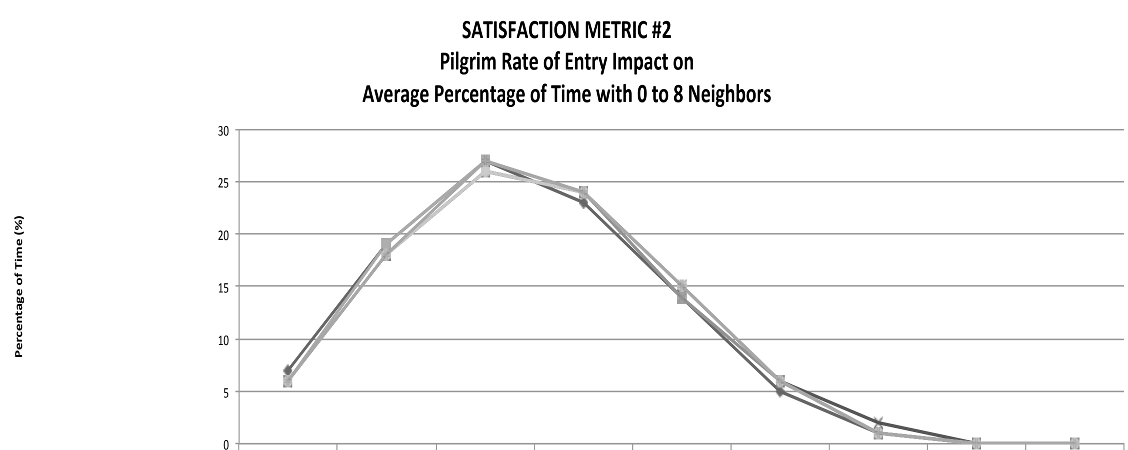
Figure 55: Gender impact on time with 0 to 8 neighbours.



	0	1	2	3	4	5	6	7	8
100% Male, 0% Female	7	18	25	23	15	6	2	0	0
75% Male, 25% Female	6	18	26	24	15	6	1	0	0
60% Male, 40% Female*	6	18	26	24	15	6	1	0	0
25% Male, 75% Female	6	18	26	24	14	6	1	0	0
0% Male, 100% Female	7	18	25	23	15	6	2	0	0

* Default scenario 1 along with scenarios 2 to 5.

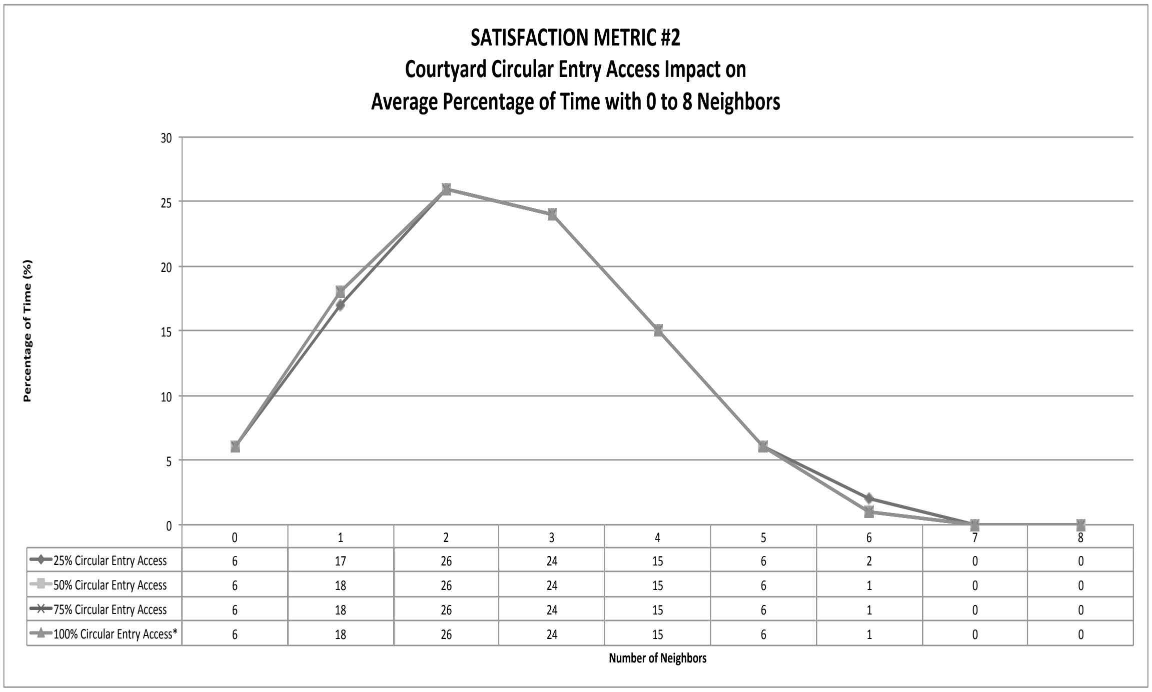
Figure 56: Rate of entry impact on time with 0 to 8 neighbours.



	0	1	2	3	4	5	6	7	8
10 Pilgrims/sec	7	19	27	23	14	5	1	0	0
15 Pilgrims/sec	6	19	27	24	14	6	1	0	0
20 Pilgrims/sec*	6	18	26	24	15	6	1	0	0
25 Pilgrims/sec	6	18	26	24	15	6	2	0	0
15- 25- 35-Pilgrims/sec burst every 300 sec	6	18	26	24	14	6	1	0	0
15- 25- 35-Pilgrims/sec burst every 600 sec	6	18	26	24	15	6	1	0	0
15- 25- 35-Pilgrims/sec burst every 900 sec	6	18	27	24	15	6	1	0	0

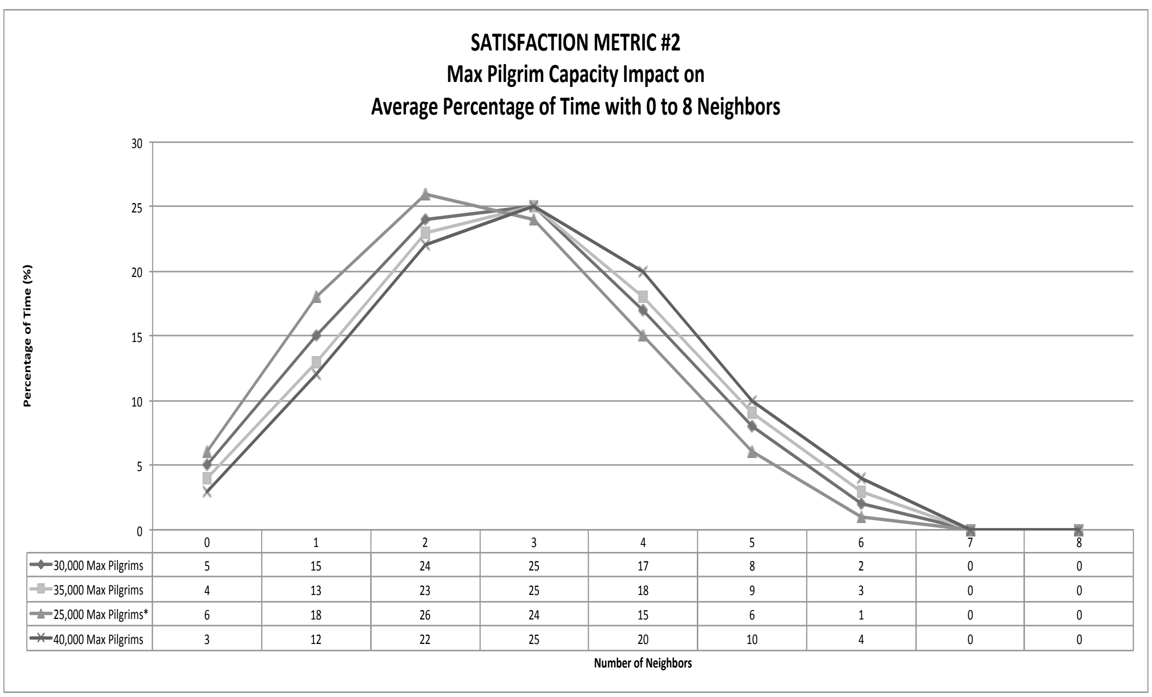
* Default scenario 1 along with scenarios 6 to 11.

Figure 57: Courtyard access impact on time with 0 to 8 neighbours.



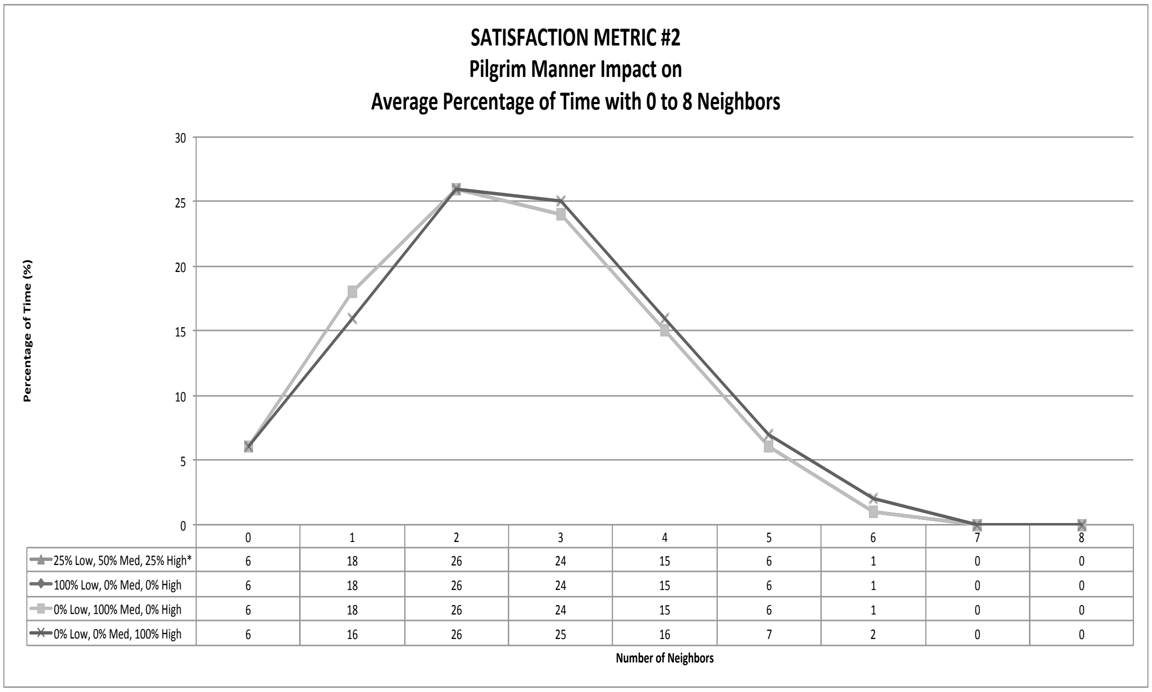
* Default scenario 1 along with scenarios 12 to 14.

Figure 58: Capacity impact on time with 0 to 8 neighbours.



* Default scenario 1 along with scenarios 15 to 17.

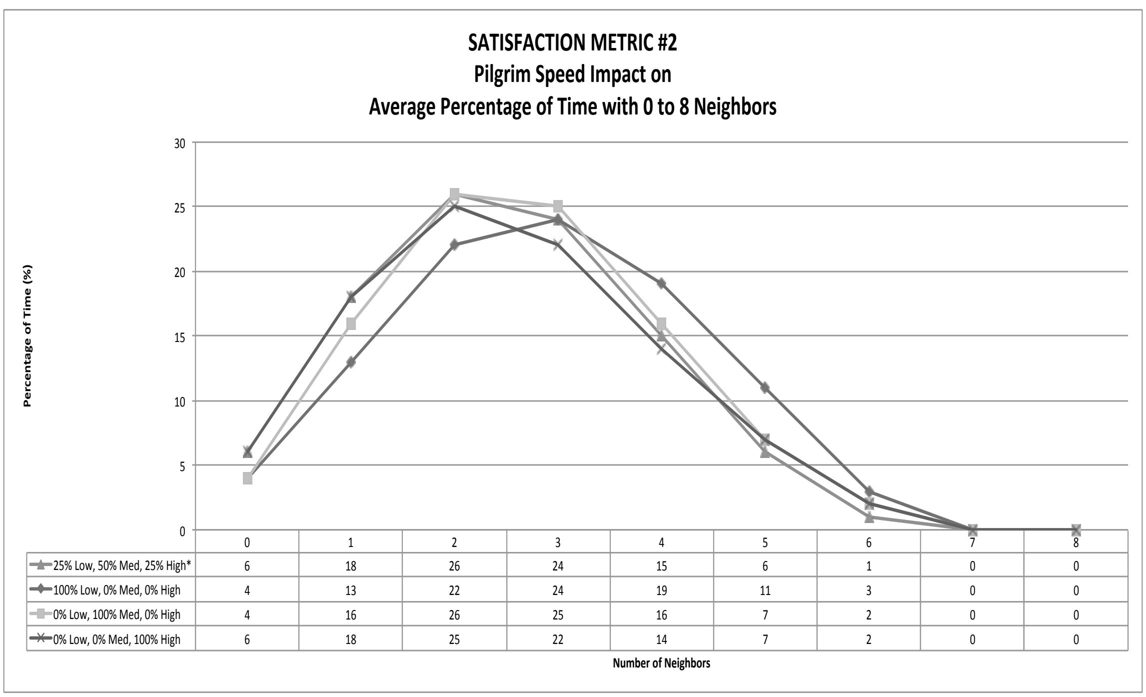
Figure 59: Manner impact on time with 0 to 8 neighbours.



	0	1	2	3	4	5	6	7	8
25% Low, 50% Med, 25% High*	6	18	26	24	15	6	1	0	0
100% Low, 0% Med, 0% High	6	18	26	24	15	6	1	0	0
0% Low, 100% Med, 0% High	6	18	26	24	15	6	1	0	0
0% Low, 0% Med, 100% High	6	16	26	25	16	7	2	0	0

* Default scenario 1 along with scenarios 18 to 20.

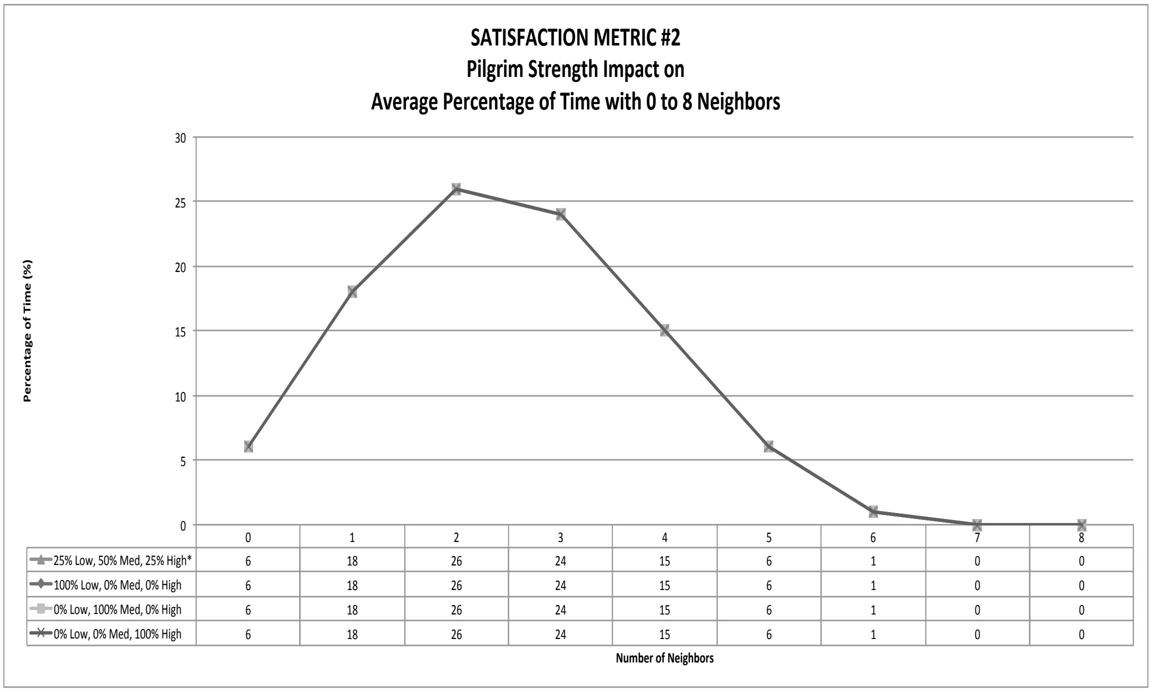
Figure 60: Speed impact on time with 0 to 8 neighbours.



	0	1	2	3	4	5	6	7	8
25% Low, 50% Med, 25% High*	6	18	26	24	15	6	1	0	0
100% Low, 0% Med, 0% High	4	13	22	24	19	11	3	0	0
0% Low, 100% Med, 0% High	4	16	26	25	16	7	2	0	0
0% Low, 0% Med, 100% High	6	18	25	22	14	7	2	0	0

* Default scenario 1 along with scenarios 21 to 23.

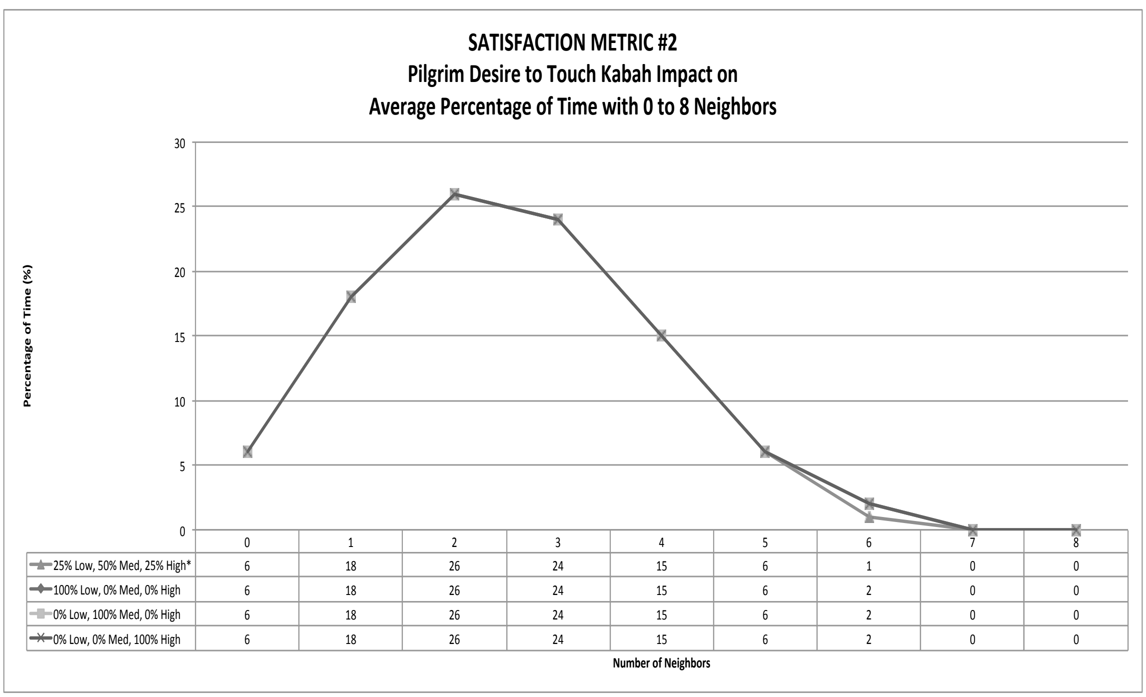
Figure 61: Strength impact on time with 0 to 8 neighbours.



	0	1	2	3	4	5	6	7	8
25% Low, 50% Med, 25% High*	6	18	26	24	15	6	1	0	0
100% Low, 0% Med, 0% High	6	18	26	24	15	6	1	0	0
0% Low, 100% Med, 0% High	6	18	26	24	15	6	1	0	0
0% Low, 0% Med, 100% High	6	18	26	24	15	6	1	0	0

* Default scenario 1 along with scenarios 24 to 26.

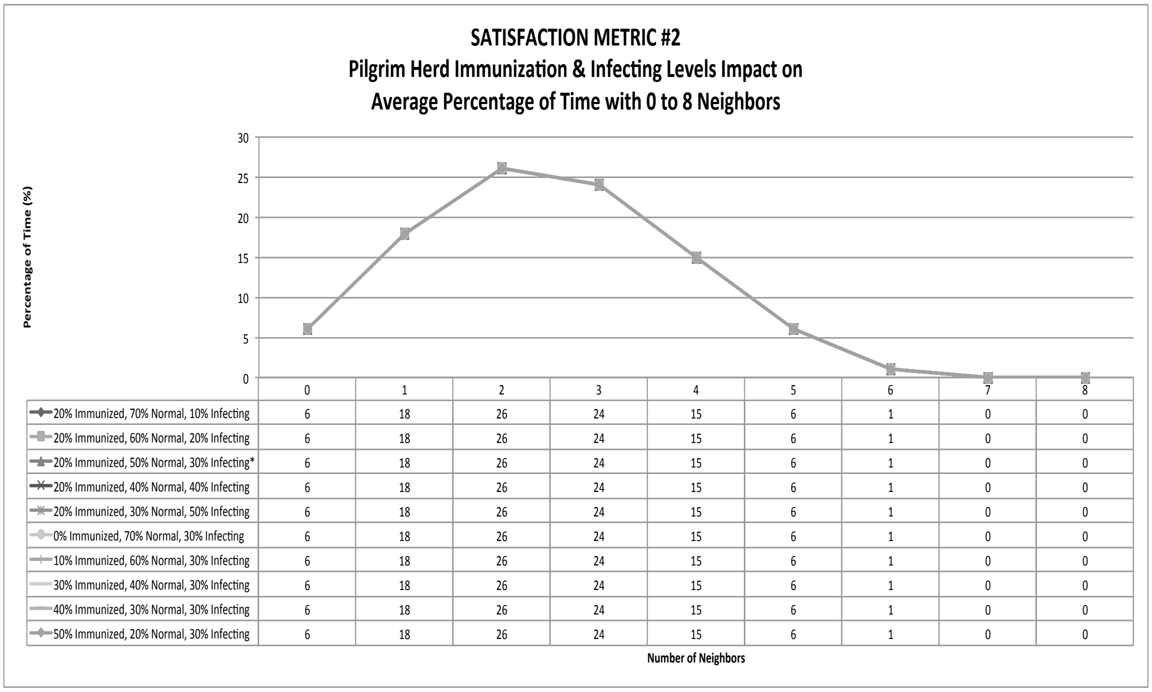
Figure 62: Desire to touch Kaaba impact on time with 0 to 8 neighbours.



	0	1	2	3	4	5	6	7	8
25% Low, 50% Med, 25% High*	6	18	26	24	15	6	1	0	0
100% Low, 0% Med, 0% High	6	18	26	24	15	6	2	0	0
0% Low, 100% Med, 0% High	6	18	26	24	15	6	2	0	0
0% Low, 0% Med, 100% High	6	18	26	24	15	6	2	0	0

* Default scenario 1 along with scenarios 27 to 29.

Figure 63: Health impact on time with 0 to 8 neighbours.



	0	1	2	3	4	5	6	7	8
20% Immunized, 70% Normal, 10% Infecting	6	18	26	24	15	6	1	0	0
20% Immunized, 60% Normal, 20% Infecting	6	18	26	24	15	6	1	0	0
20% Immunized, 50% Normal, 30% Infecting*	6	18	26	24	15	6	1	0	0
20% Immunized, 40% Normal, 40% Infecting	6	18	26	24	15	6	1	0	0
20% Immunized, 30% Normal, 50% Infecting	6	18	26	24	15	6	1	0	0
0% Immunized, 70% Normal, 30% Infecting	6	18	26	24	15	6	1	0	0
10% Immunized, 60% Normal, 30% Infecting	6	18	26	24	15	6	1	0	0
30% Immunized, 40% Normal, 30% Infecting	6	18	26	24	15	6	1	0	0
40% Immunized, 30% Normal, 30% Infecting	6	18	26	24	15	6	1	0	0
50% Immunized, 20% Normal, 30% Infecting	6	18	26	24	15	6	1	0	0

* Default scenario 1 along with scenarios 30 to 38.

Figure 64: Degree of spiralling impact on time with 0 to 8 neighbours.

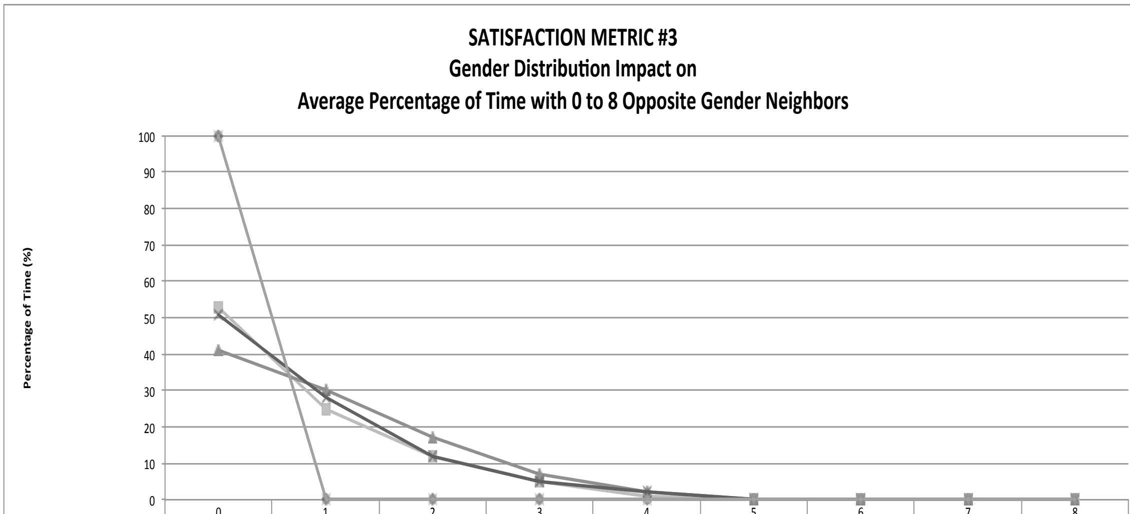
	0	1	2	3	4	5	6	7	8
100% n=1, 0% n=2, 0% n=3, 0% n=4	5	12	16	19	19	15	8	2	0
0% n=1, 100% n=2, 0% n=3, 0% n=4	4	12	21	24	19	11	4	1	0
25% n=1, 25% n=2, 25% n=3, 25% n=4*	6	18	26	24	15	6	1	0	0
0% n=1, 0% n=2, 100% n=3, 0% n=4	3	12	22	25	20	10	3	0	0
0% n=1, 0% n=2, 0% n=3, 100% n=4	5	14	21	22	17	10	5	1	0

* Default scenario 1 along with scenarios 39 to 42.

Appendix D:

TawafSIM Satisfaction Metric #3 Figures

Figure 65: Gender impact on time with opposite gender neighbours.

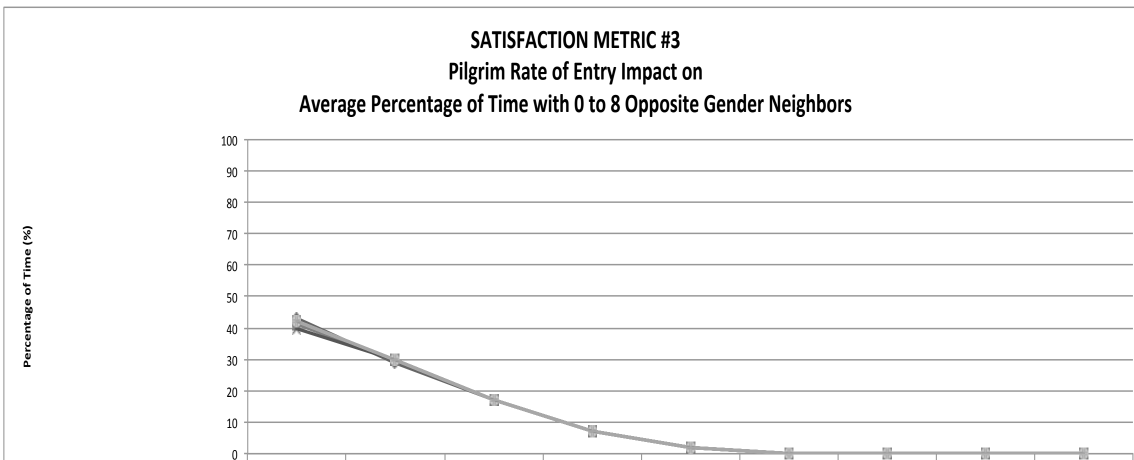


	0	1	2	3	4	5	6	7	8
100% Male, 0% Female	100	0	0	0	0	0	0	0	0
75% Male, 25% Female	53	25	12	5	1	0	0	0	0
60% Male, 40% Female*	41	30	17	7	2	0	0	0	0
25% Male, 75% Female	51	28	12	5	2	0	0	0	0
0% Male, 100% Female	100	0	0	0	0	0	0	0	0

Number of Opposite Gender Neighbors

* Default scenario 1 along with scenarios 2 to 5.

Figure 66: Rate of entry impact on time with opposite gender neighbours.

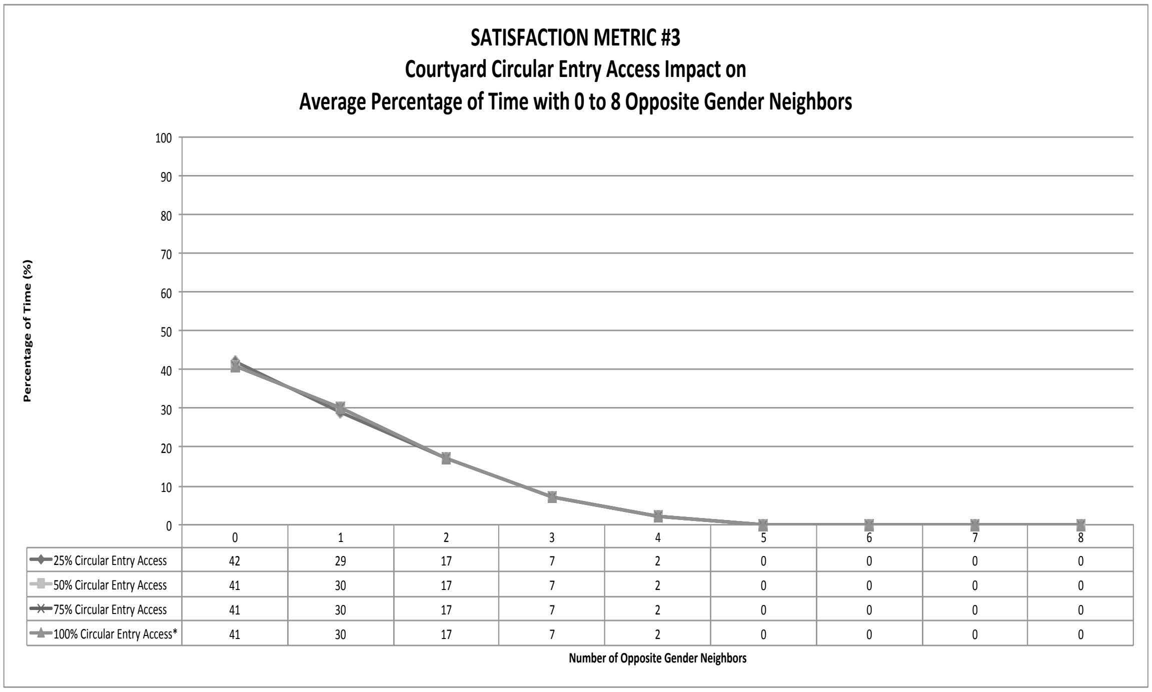


	0	1	2	3	4	5	6	7	8
10 Pilgrims/sec	43	29	17	7	2	0	0	0	0
15 Pilgrims/sec	42	30	17	7	2	0	0	0	0
20 Pilgrims/sec*	41	30	17	7	2	0	0	0	0
25 Pilgrims/sec	40	30	17	7	2	0	0	0	0
15- 25- 35-Pilgrims/sec burst every 300 sec	42	30	17	7	2	0	0	0	0
15- 25- 35-Pilgrims/sec burst every 600 sec	42	30	17	7	2	0	0	0	0
15- 25- 35-Pilgrims/sec burst every 900 sec	42	30	17	7	2	0	0	0	0

Number of Opposite Gender Neighbors

* Default scenario 1 along with scenarios 6 to 11.

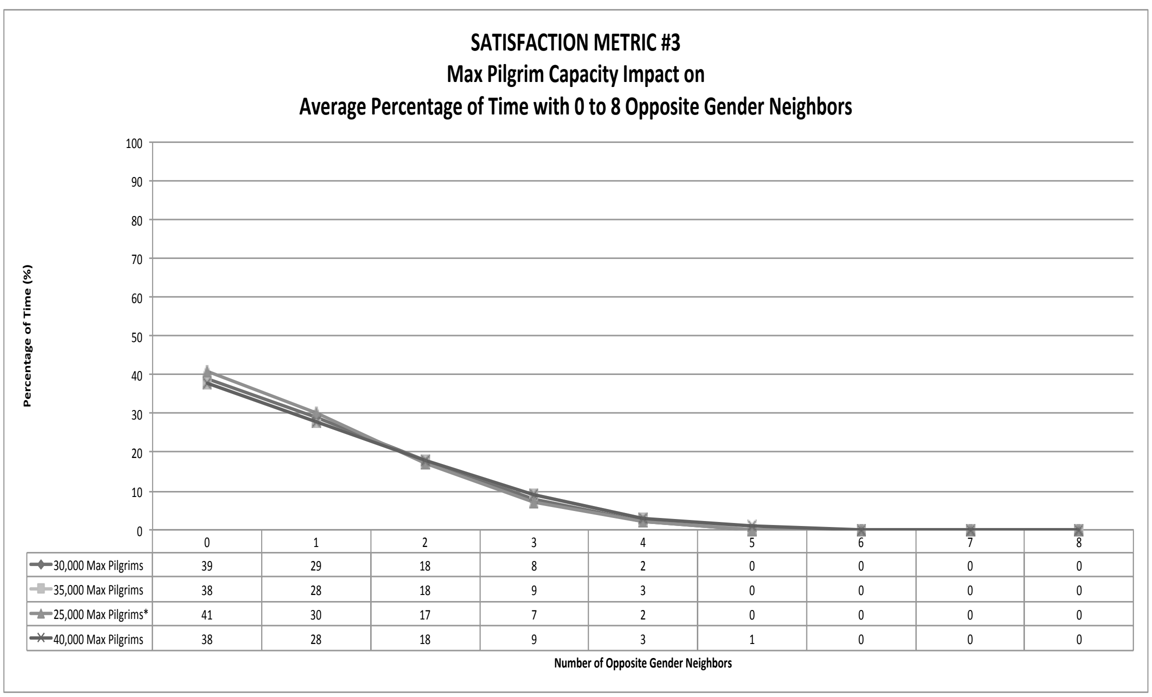
Figure 67: Courtyard access impact on time with opposite gender neighbours.



	0	1	2	3	4	5	6	7	8
25% Circular Entry Access	42	29	17	7	2	0	0	0	0
50% Circular Entry Access	41	30	17	7	2	0	0	0	0
75% Circular Entry Access	41	30	17	7	2	0	0	0	0
100% Circular Entry Access*	41	30	17	7	2	0	0	0	0

* Default scenario 1 along with scenarios 12 to 14.

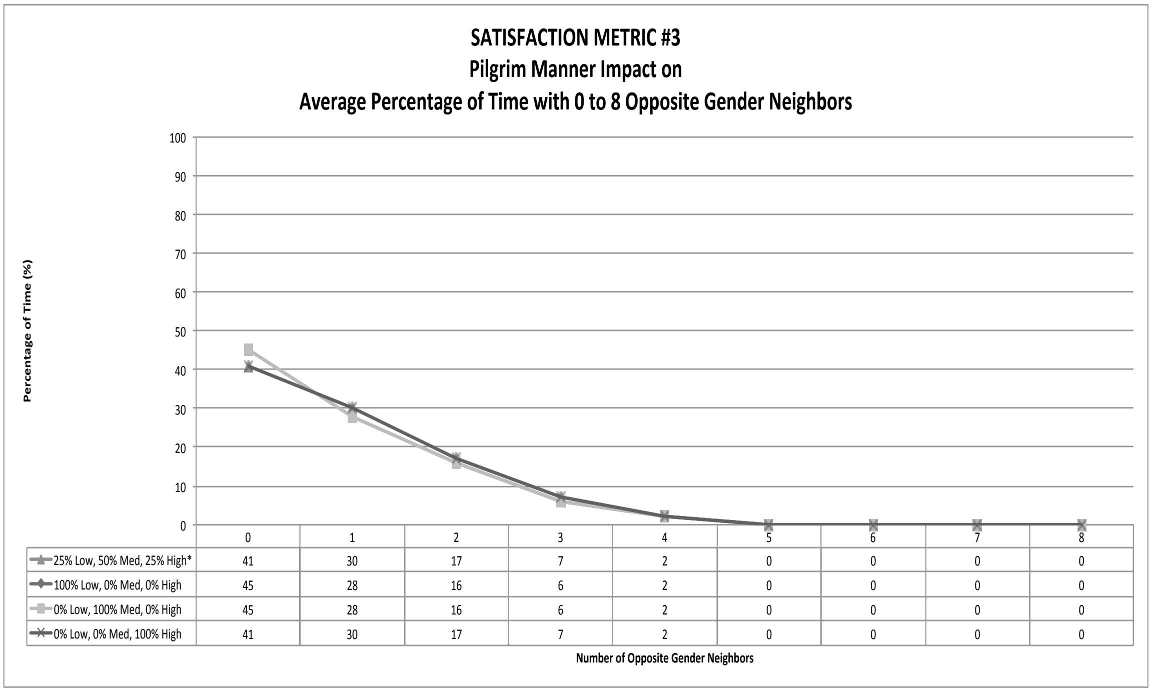
Figure 68: Capacity impact on time with opposite gender neighbours.



	0	1	2	3	4	5	6	7	8
30,000 Max Pilgrims	39	29	18	8	2	0	0	0	0
35,000 Max Pilgrims	38	28	18	9	3	0	0	0	0
25,000 Max Pilgrims*	41	30	17	7	2	0	0	0	0
40,000 Max Pilgrims	38	28	18	9	3	1	0	0	0

* Default scenario 1 along with scenarios 15 to 17.

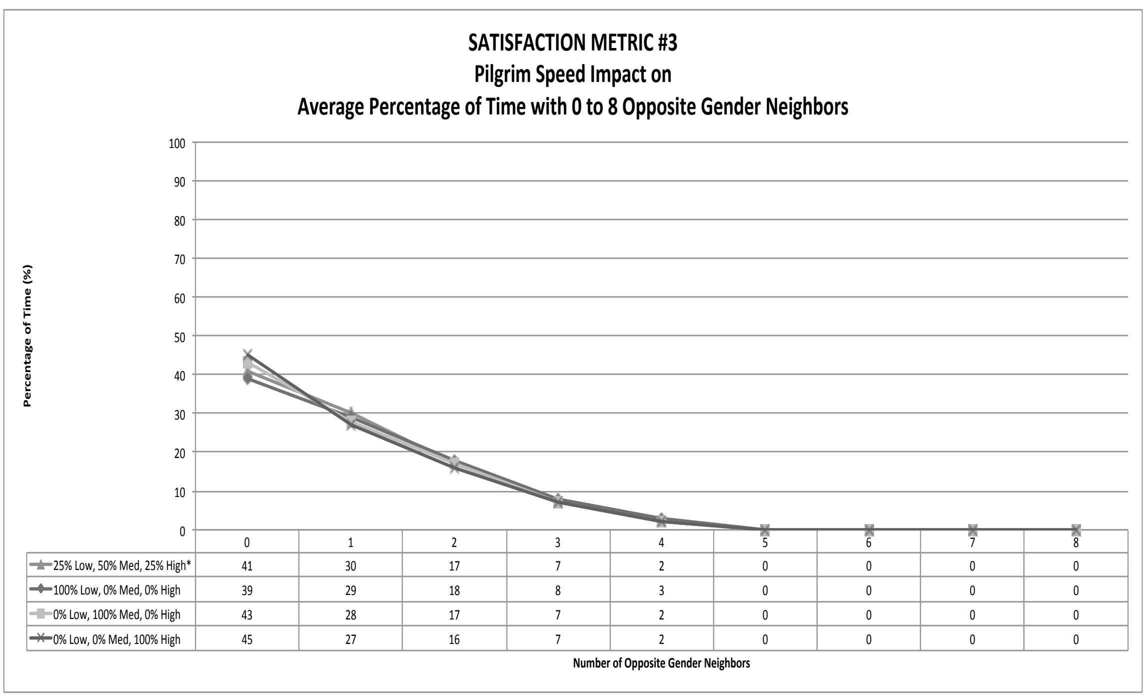
Figure 69: Manner impact on time with opposite gender neighbours.



	0	1	2	3	4	5	6	7	8
25% Low, 50% Med, 25% High*	41	30	17	7	2	0	0	0	0
100% Low, 0% Med, 0% High	45	28	16	6	2	0	0	0	0
0% Low, 100% Med, 0% High	45	28	16	6	2	0	0	0	0
0% Low, 0% Med, 100% High	41	30	17	7	2	0	0	0	0

* Default scenario 1 along with scenarios 18 to 20.

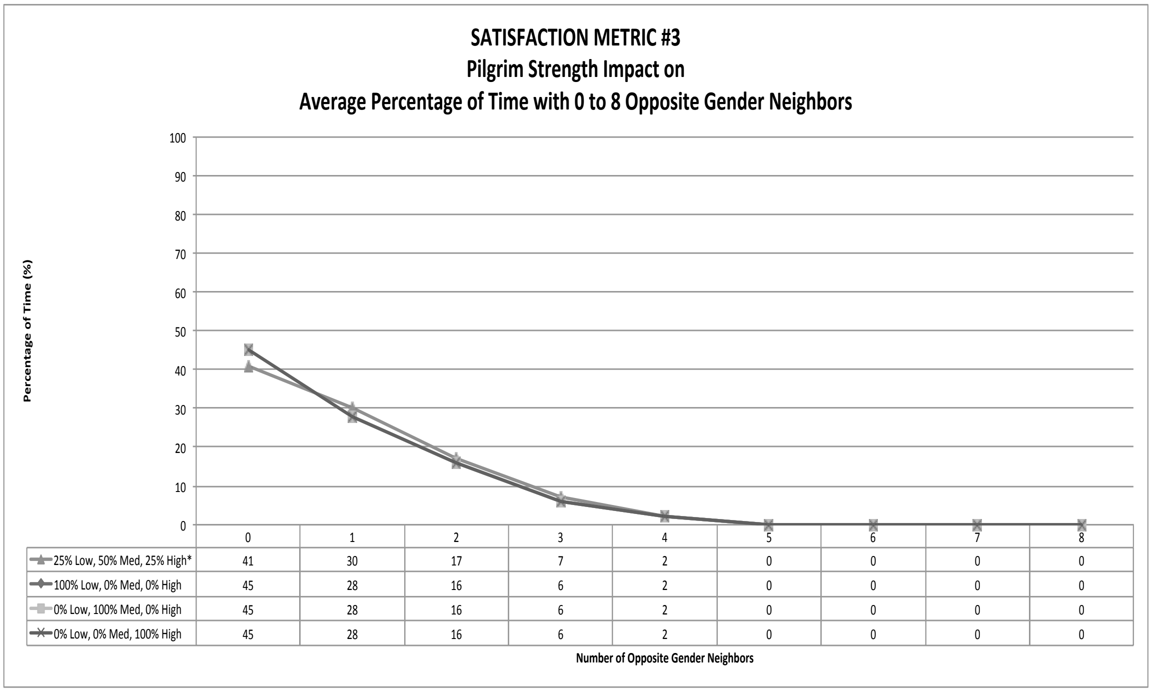
Figure 70: Speed impact on time with opposite gender neighbours.



	0	1	2	3	4	5	6	7	8
25% Low, 50% Med, 25% High*	41	30	17	7	2	0	0	0	0
100% Low, 0% Med, 0% High	39	29	18	8	3	0	0	0	0
0% Low, 100% Med, 0% High	43	28	17	7	2	0	0	0	0
0% Low, 0% Med, 100% High	45	27	16	7	2	0	0	0	0

* Default scenario 1 along with scenarios 21 to 23.

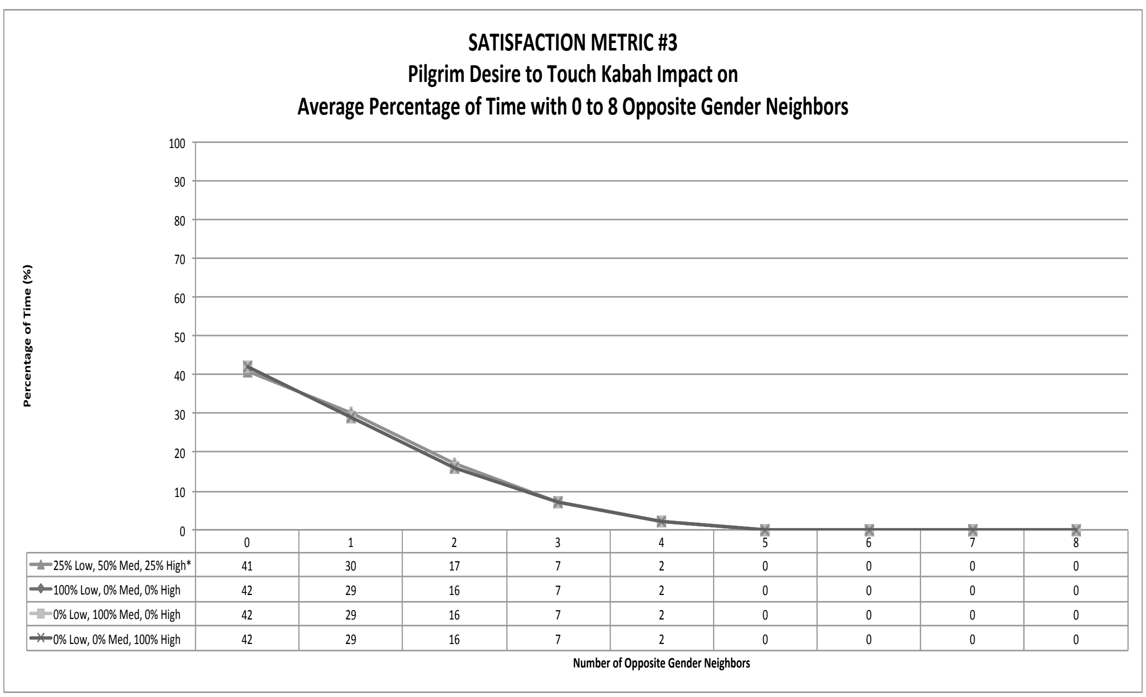
Figure 71: Strength impact on time with opposite gender neighbours.



	0	1	2	3	4	5	6	7	8
25% Low, 50% Med, 25% High*	41	30	17	7	2	0	0	0	0
100% Low, 0% Med, 0% High	45	28	16	6	2	0	0	0	0
0% Low, 100% Med, 0% High	45	28	16	6	2	0	0	0	0
0% Low, 0% Med, 100% High	45	28	16	6	2	0	0	0	0

* Default scenario 1 along with scenarios 24 to 26.

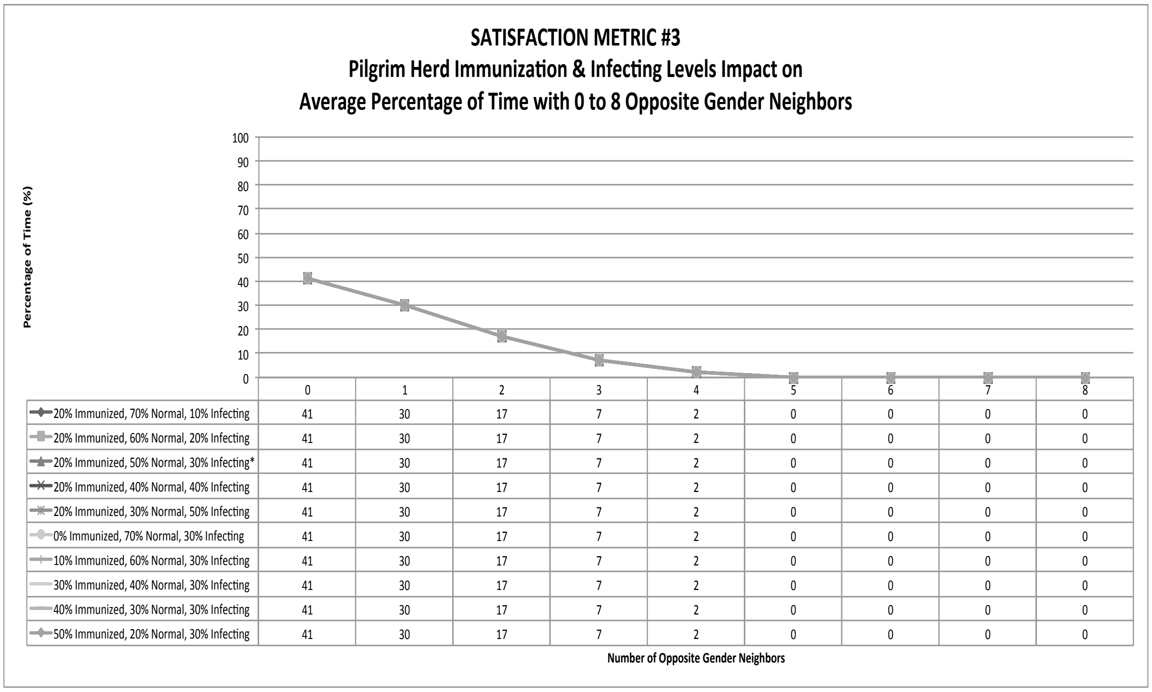
Figure 72: Desire to touch Kaaba impact on time with opposite gender neighbours.



	0	1	2	3	4	5	6	7	8
25% Low, 50% Med, 25% High*	41	30	17	7	2	0	0	0	0
100% Low, 0% Med, 0% High	42	29	16	7	2	0	0	0	0
0% Low, 100% Med, 0% High	42	29	16	7	2	0	0	0	0
0% Low, 0% Med, 100% High	42	29	16	7	2	0	0	0	0

* Default scenario 1 along with scenarios 27 to 29.

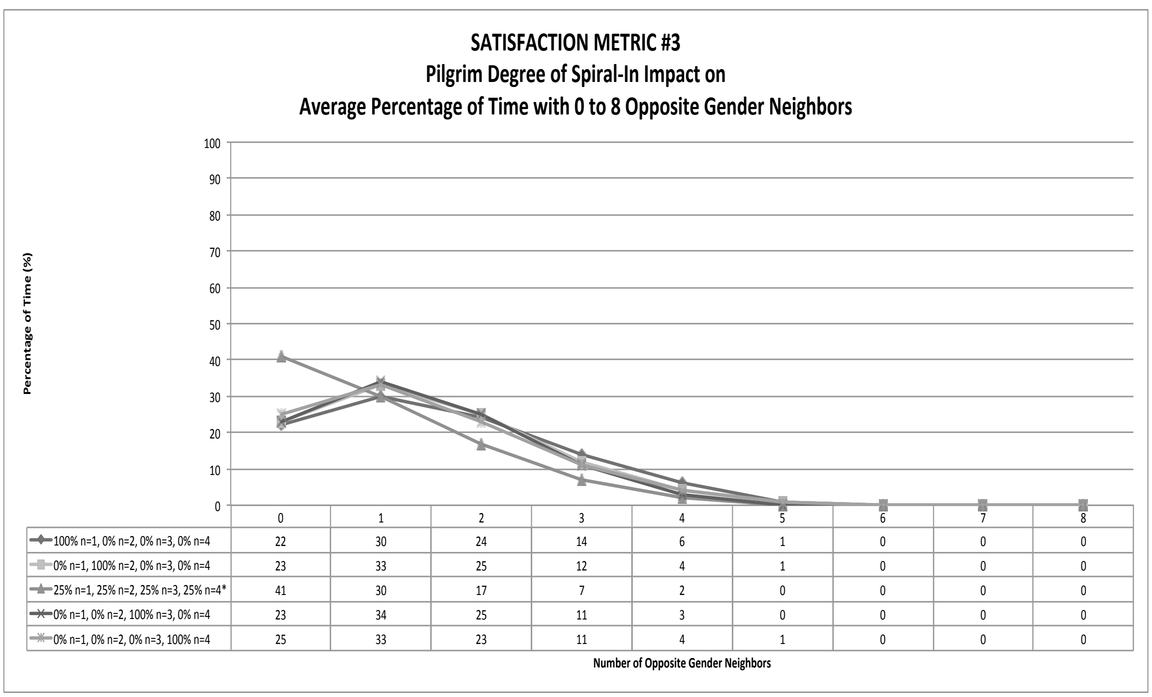
Figure 73: Health impact on time with opposite gender neighbours.



	0	1	2	3	4	5	6	7	8
20% Immunized, 70% Normal, 10% Infecting	41	30	17	7	2	0	0	0	0
20% Immunized, 60% Normal, 20% Infecting	41	30	17	7	2	0	0	0	0
20% Immunized, 50% Normal, 30% Infecting*	41	30	17	7	2	0	0	0	0
20% Immunized, 40% Normal, 40% Infecting	41	30	17	7	2	0	0	0	0
20% Immunized, 30% Normal, 50% Infecting	41	30	17	7	2	0	0	0	0
0% Immunized, 70% Normal, 30% Infecting	41	30	17	7	2	0	0	0	0
10% Immunized, 60% Normal, 30% Infecting	41	30	17	7	2	0	0	0	0
30% Immunized, 40% Normal, 30% Infecting	41	30	17	7	2	0	0	0	0
40% Immunized, 30% Normal, 30% Infecting	41	30	17	7	2	0	0	0	0
50% Immunized, 20% Normal, 30% Infecting	41	30	17	7	2	0	0	0	0

* Default scenario 1 along with scenarios 30 to 38.

Figure 74: Degree of spiralling impact on time with opposite gender neighbours.



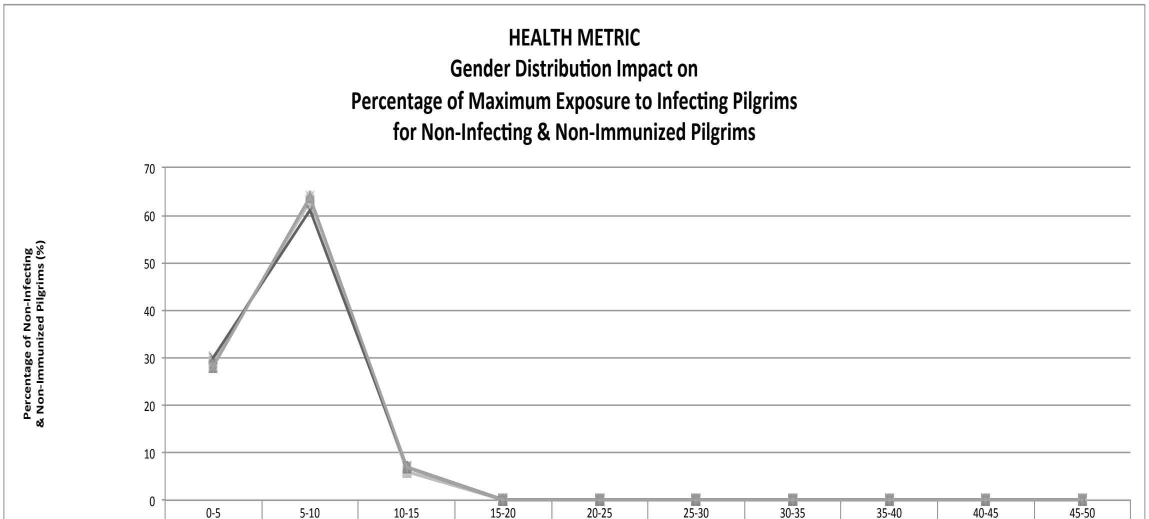
	0	1	2	3	4	5	6	7	8
100% n=1, 0% n=2, 0% n=3, 0% n=4	22	30	24	14	6	1	0	0	0
0% n=1, 100% n=2, 0% n=3, 0% n=4	23	33	25	12	4	1	0	0	0
25% n=1, 25% n=2, 25% n=3, 25% n=4*	41	30	17	7	2	0	0	0	0
0% n=1, 0% n=2, 100% n=3, 0% n=4	23	34	25	11	3	0	0	0	0
0% n=1, 0% n=2, 0% n=3, 100% n=4	25	33	23	11	4	1	0	0	0

* Default scenario 1 along with scenarios 39 to 42.

Appendix E:

TawafSIM Health Metric Figures

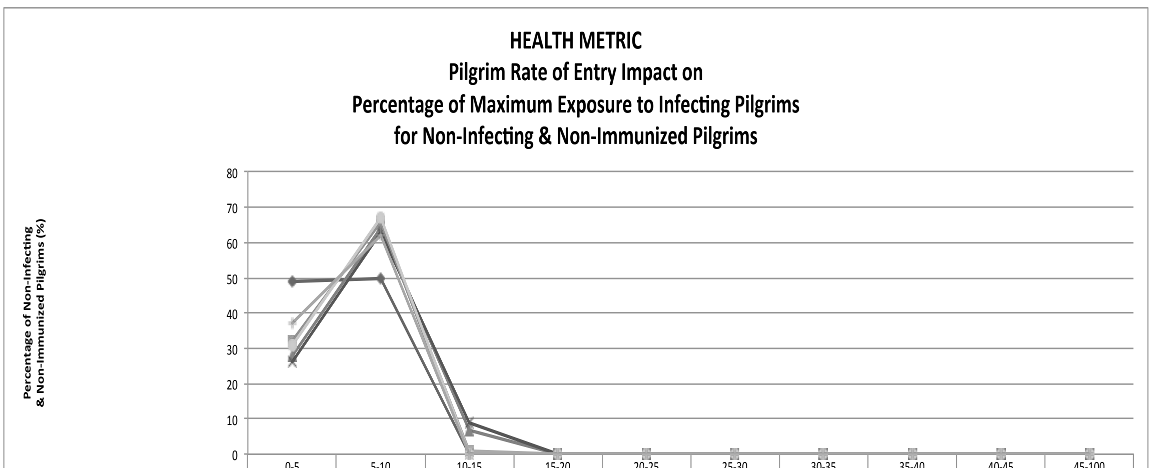
Figure 75: Gender impact on infectious disease exposure.



	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	45-50
100% Male, 0% Female	29	63	7	0	0	0	0	0	0	0
75% Male, 25% Female	29	63	6	0	0	0	0	0	0	0
60% Male, 40% Female*	28	64	7	0	0	0	0	0	0	0
25% Male, 75% Female	30	61	7	0	0	0	0	0	0	0
0% Male, 100% Female	28	64	7	0	0	0	0	0	0	0

* Default scenario 1 along with scenarios 2 to 5.

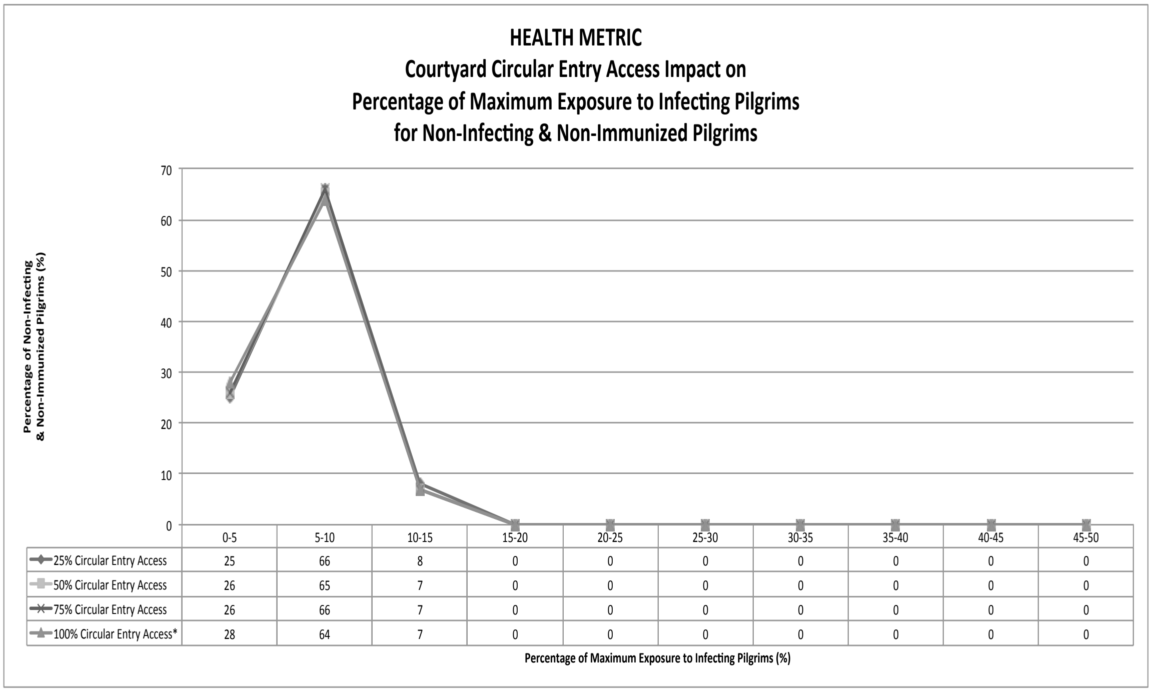
Figure 76: Rate of entry impact on infectious disease exposure.



	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	45-100
10 Pilgrims/sec	49	50	0	0	0	0	0	0	0	0
15 Pilgrims/sec	32	66	1	0	0	0	0	0	0	0
20 Pilgrims/sec*	28	64	7	0	0	0	0	0	0	0
25 Pilgrims/sec	26	63	9	0	0	0	0	0	0	0
15- 25- 35-Pilgrims/sec burst every 300 sec	32	66	0	0	0	0	0	0	0	0
15- 25- 35-Pilgrims/sec burst every 600 sec	31	67	0	0	0	0	0	0	0	0
15- 25- 35-Pilgrims/sec burst every 900 sec	37	62	0	0	0	0	0	0	0	0

* Default scenario 1 along with scenarios 6 to 11.

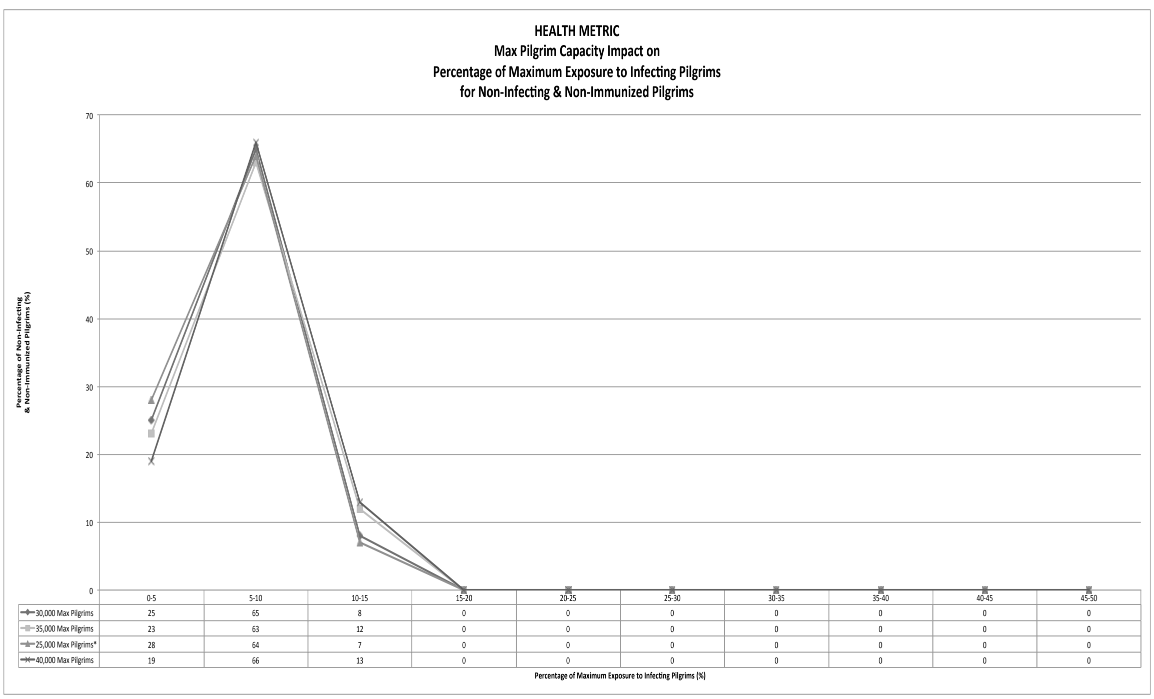
Figure 77: Courtyard access impact on infectious disease exposure.



	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	45-50
25% Circular Entry Access	25	66	8	0	0	0	0	0	0	0
50% Circular Entry Access	26	65	7	0	0	0	0	0	0	0
75% Circular Entry Access	26	66	7	0	0	0	0	0	0	0
100% Circular Entry Access*	28	64	7	0	0	0	0	0	0	0

* Default scenario 1 along with scenarios 12 to 14.

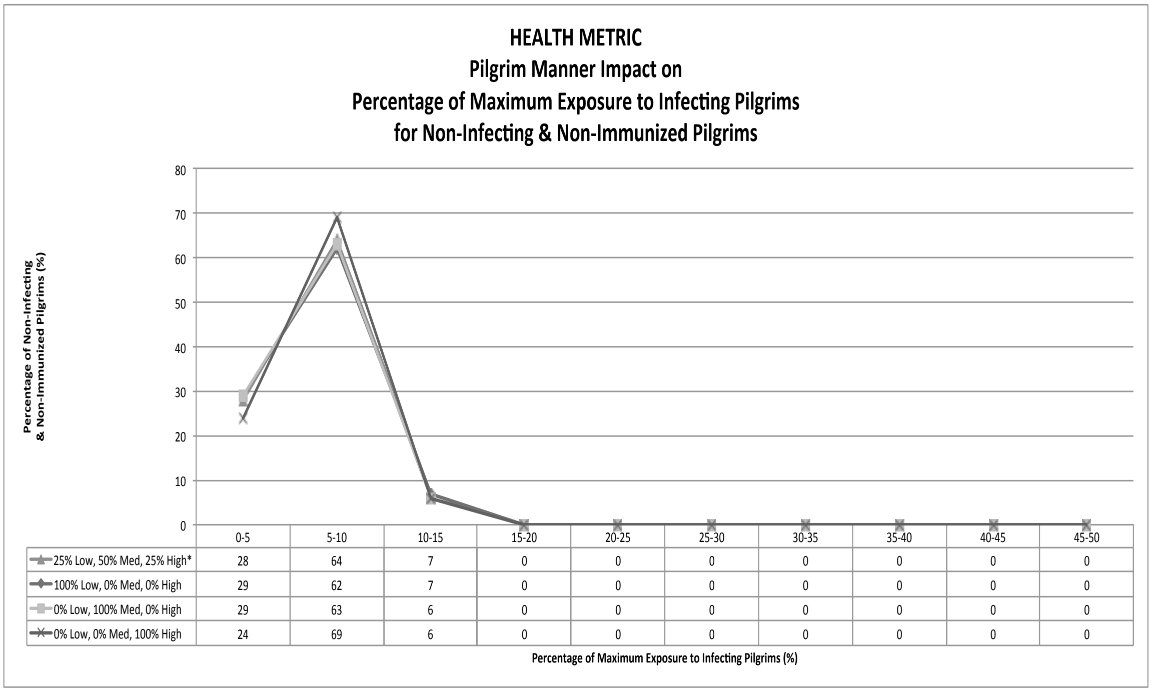
Figure 78: Capacity impact on infectious disease exposure.



	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	45-50
30,000 Max Pilgrims	25	65	8	0	0	0	0	0	0	0
35,000 Max Pilgrims	23	63	12	0	0	0	0	0	0	0
25,000 Max Pilgrims*	28	64	7	0	0	0	0	0	0	0
40,000 Max Pilgrims	19	66	13	0	0	0	0	0	0	0

* Default scenario 1 along with scenarios 15 to 17.

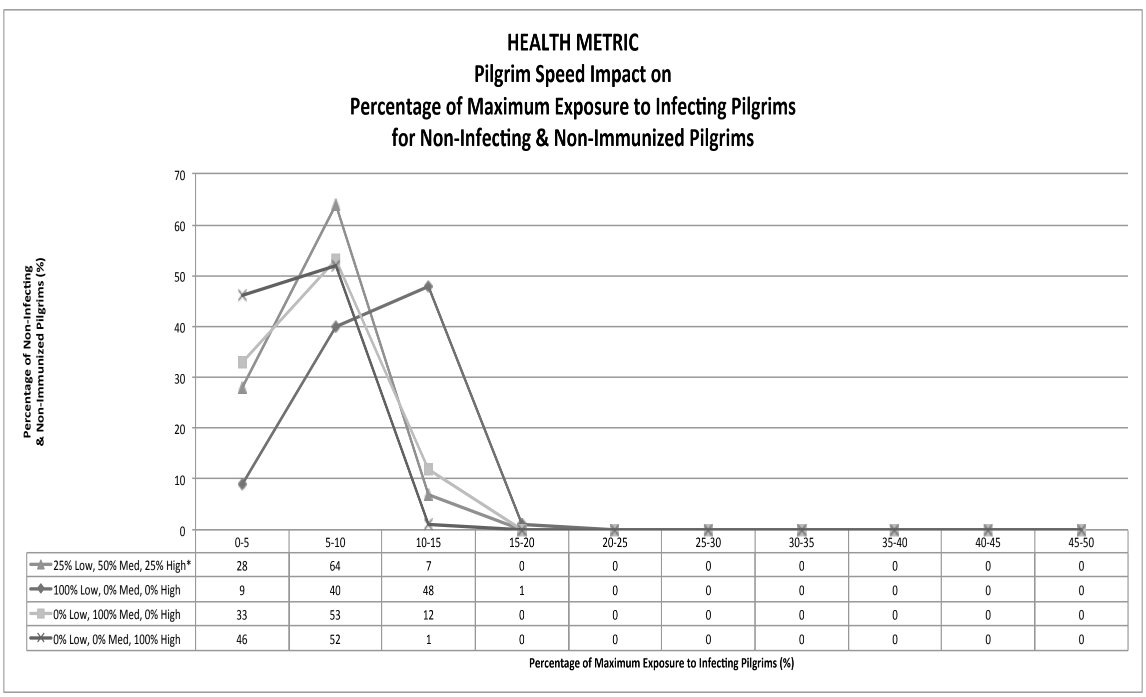
Figure 79: Manner impact on infectious disease exposure.



	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	45-50
25% Low, 50% Med, 25% High*	28	64	7	0	0	0	0	0	0	0
100% Low, 0% Med, 0% High	29	62	7	0	0	0	0	0	0	0
0% Low, 100% Med, 0% High	29	63	6	0	0	0	0	0	0	0
0% Low, 0% Med, 100% High	24	69	6	0	0	0	0	0	0	0

* Default scenario 1 along with scenarios 18 to 20.

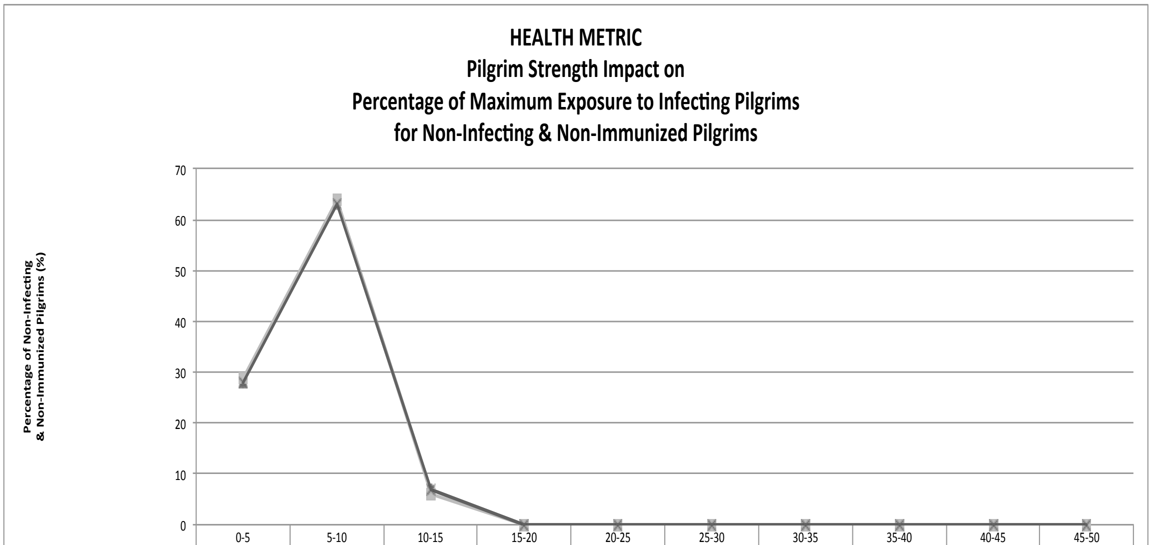
Figure 80: Speed impact on infectious disease exposure.



	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	45-50
25% Low, 50% Med, 25% High*	28	64	7	0	0	0	0	0	0	0
100% Low, 0% Med, 0% High	9	40	48	1	0	0	0	0	0	0
0% Low, 100% Med, 0% High	33	53	12	0	0	0	0	0	0	0
0% Low, 0% Med, 100% High	46	52	1	0	0	0	0	0	0	0

* Default scenario 1 along with scenarios 21 to 23.

Figure 81: Strength impact on infectious disease exposure.

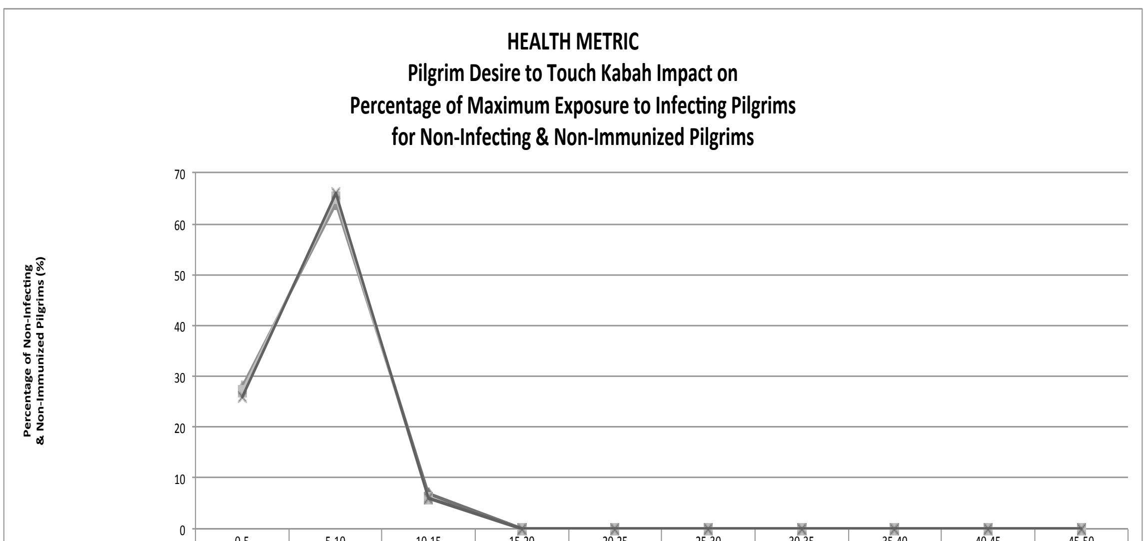


	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	45-50
25% Low, 50% Med, 25% High*	28	64	7	0	0	0	0	0	0	0
100% Low, 0% Med, 0% High	28	63	7	0	0	0	0	0	0	0
0% Low, 100% Med, 0% High	29	64	6	0	0	0	0	0	0	0
0% Low, 0% Med, 100% High	28	63	7	0	0	0	0	0	0	0

Percentage of Maximum Exposure to Infecting Pilgrims (%)

* Default scenario 1 along with scenarios 24 to 26.

Figure 82: Desire to touch Kaaba impact on infectious disease exposure.

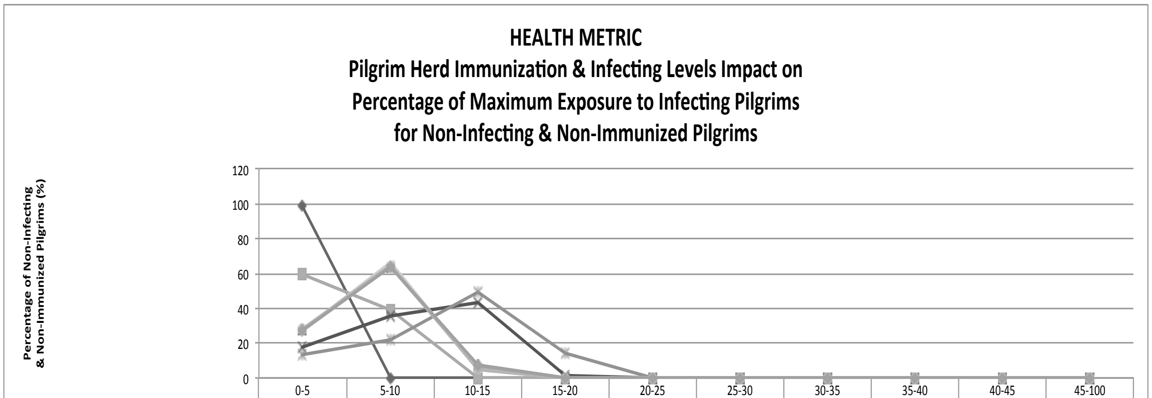


	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	45-50
25% Low, 50% Med, 25% High*	28	64	7	0	0	0	0	0	0	0
100% Low, 0% Med, 0% High	27	65	7	0	0	0	0	0	0	0
0% Low, 100% Med, 0% High	27	65	6	0	0	0	0	0	0	0
0% Low, 0% Med, 100% High	26	66	6	0	0	0	0	0	0	0

Percentage of Maximum Exposure to Infecting Pilgrims (%)

* Default scenario 1 along with scenarios 27 to 29.

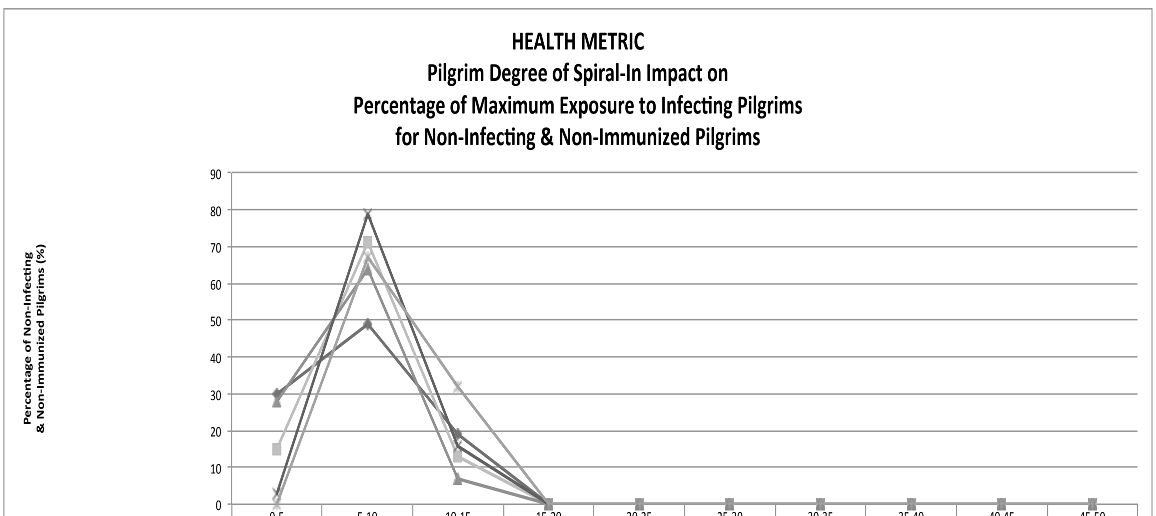
Figure 83: Health impact on infectious disease exposure.



	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	45-100
20% Immunized, 70% Normal, 10% Infecting	99	0	0	0	0	0	0	0	0	0
20% Immunized, 60% Normal, 20% Infecting	60	39	0	0	0	0	0	0	0	0
20% Immunized, 50% Normal, 30% Infecting*	28	64	7	0	0	0	0	0	0	0
20% Immunized, 40% Normal, 40% Infecting	18	36	43	1	0	0	0	0	0	0
20% Immunized, 30% Normal, 50% Infecting	13	22	49	14	0	0	0	0	0	0
0% Immunized, 70% Normal, 30% Infecting	28	64	6	0	0	0	0	0	0	0
10% Immunized, 60% Normal, 30% Infecting	28	64	6	0	0	0	0	0	0	0
30% Immunized, 40% Normal, 30% Infecting	27	66	5	0	0	0	0	0	0	0
40% Immunized, 30% Normal, 30% Infecting	28	65	5	0	0	0	0	0	0	0
50% Immunized, 20% Normal, 30% Infecting	27	64	7	0	0	0	0	0	0	0

* Default scenario 1 along with scenarios 30 to 38.

Figure 84: Degree of spiralling impact on infectious disease exposure.



	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	45-50
100% n=1, 0% n=2, 0% n=3, 0% n=4	30	49	19	0	0	0	0	0	0	0
0% n=1, 100% n=2, 0% n=3, 0% n=4	15	71	13	0	0	0	0	0	0	0
25% n=1, 25% n=2, 25% n=3, 25% n=4*	28	64	7	0	0	0	0	0	0	0
0% n=1, 0% n=2, 100% n=3, 0% n=4	3	79	16	0	0	0	0	0	0	0
0% n=1, 0% n=2, 0% n=3, 100% n=4	0	67	32	0	0	0	0	0	0	0

* Default scenario 1 along with scenarios 39 to 42.

Appendix F:

TawafSIM Safety Metric Figures

Figure 85: Safety plots for scenario 1

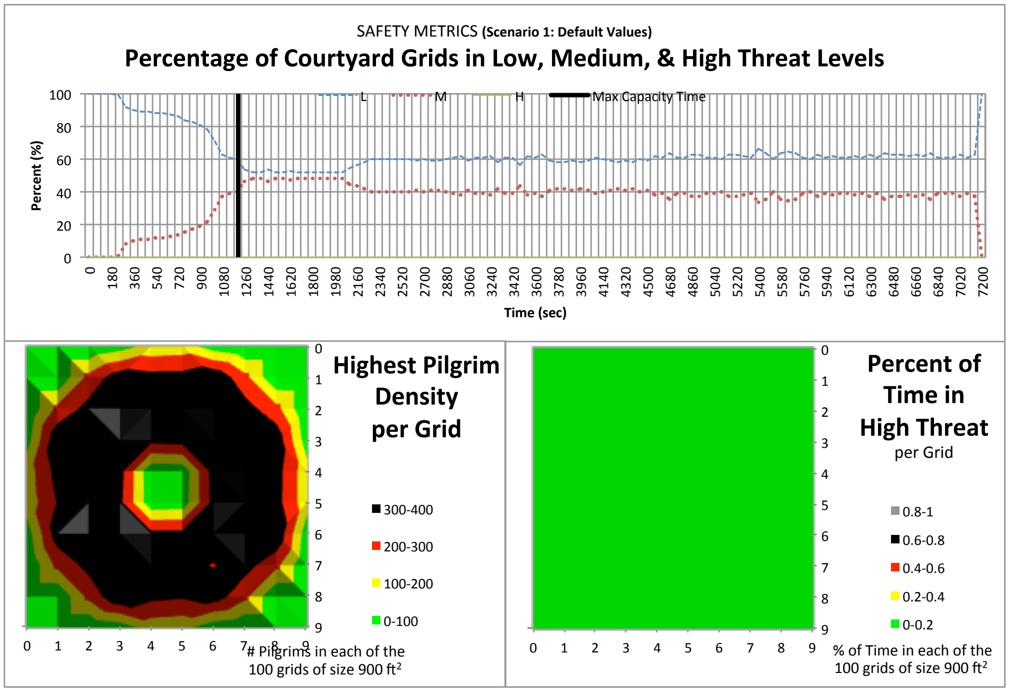


Figure 86: Safety plots for scenario 6

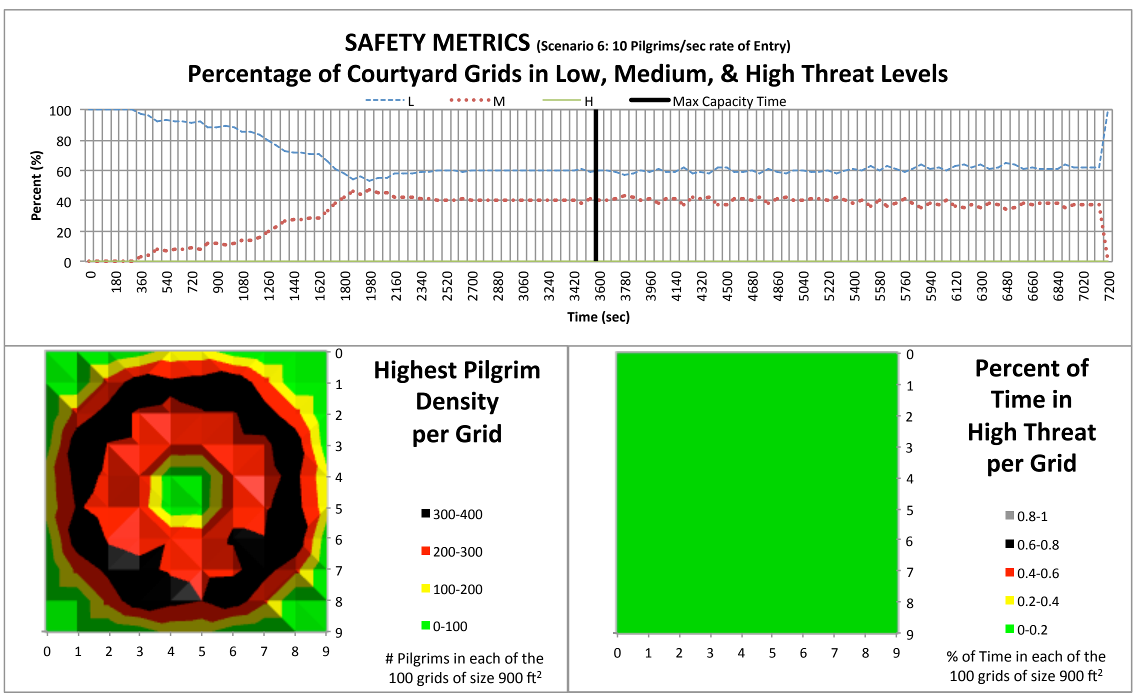


Figure 87: Safety plots for scenario 11

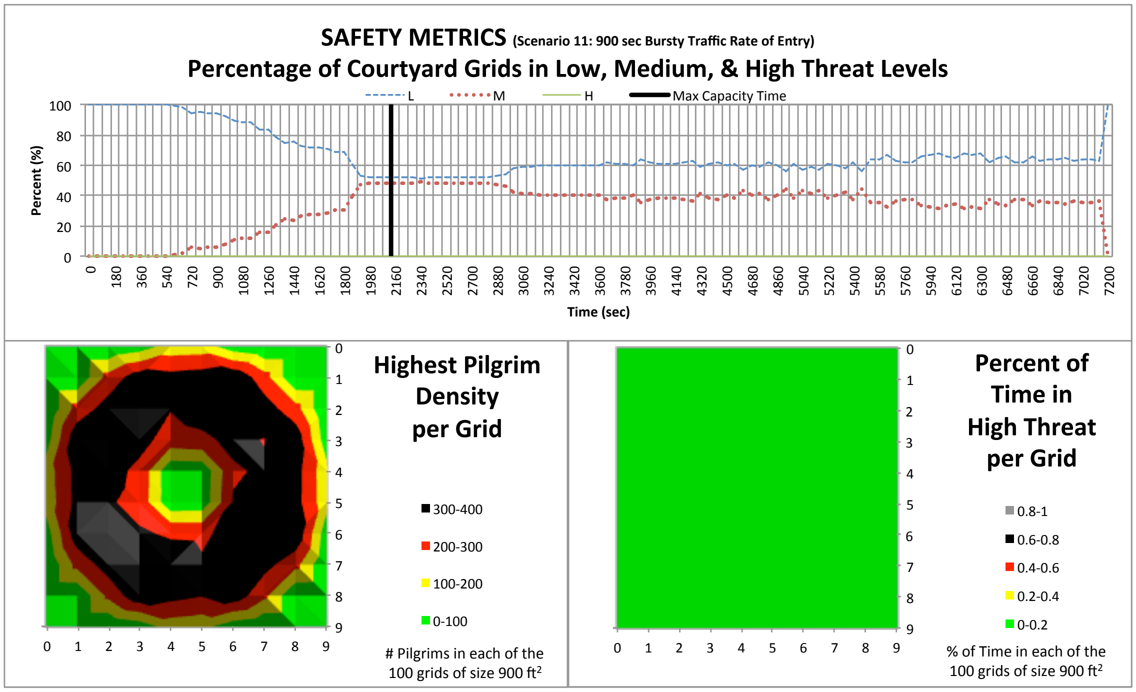


Figure 88: Safety plots for scenario 15

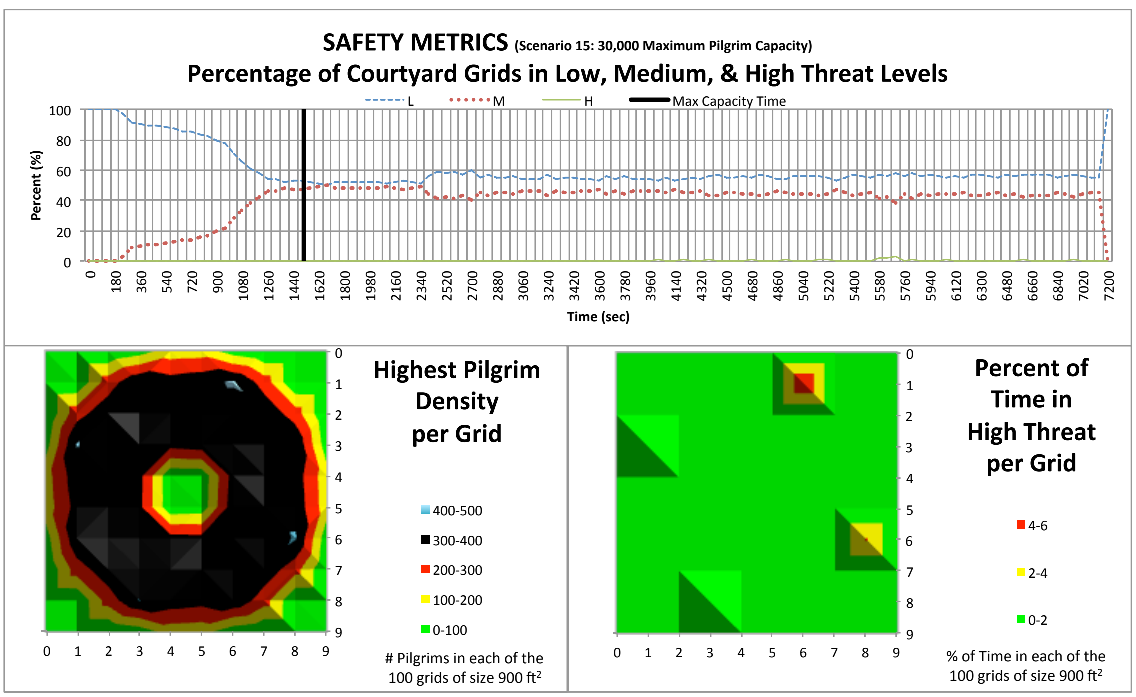


Figure 89: Safety plots for scenario 16

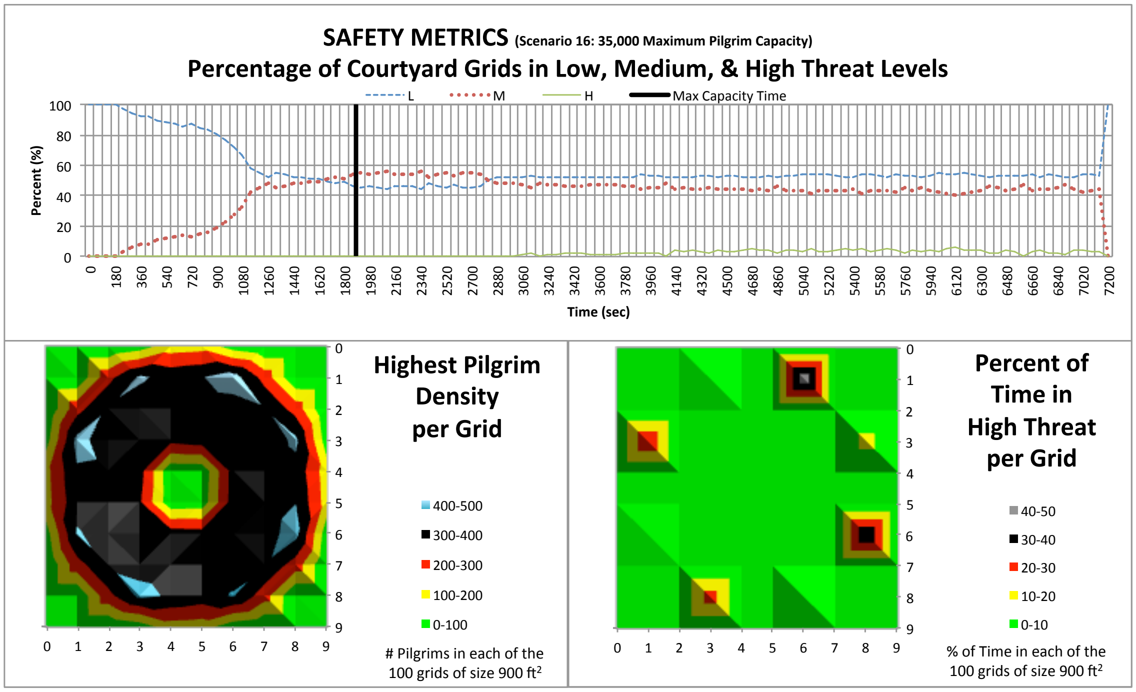


Figure 90: Safety plots for scenario 17

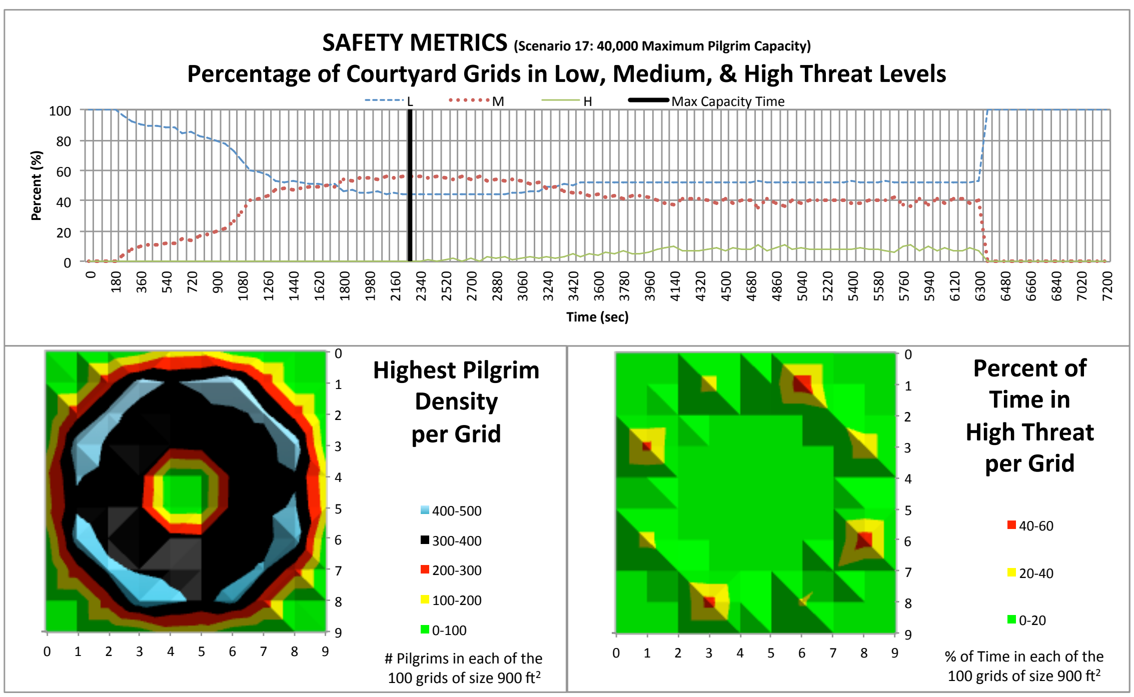


Figure 91: Safety plots for scenario 21

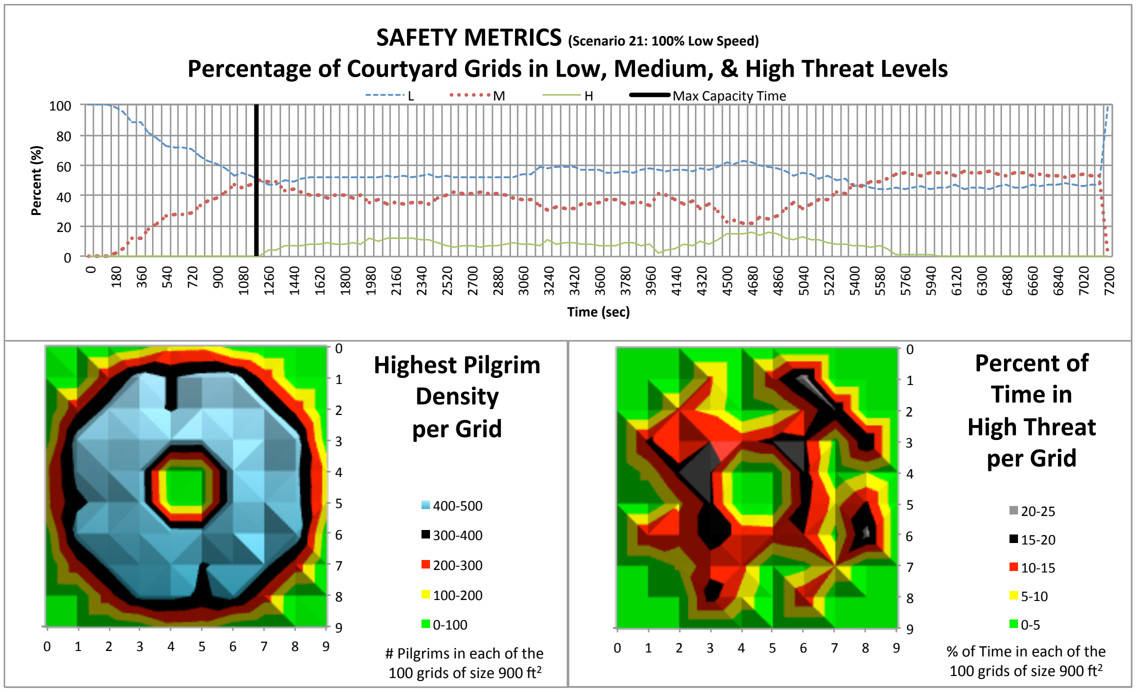


Figure 92: Safety plots for scenario 22

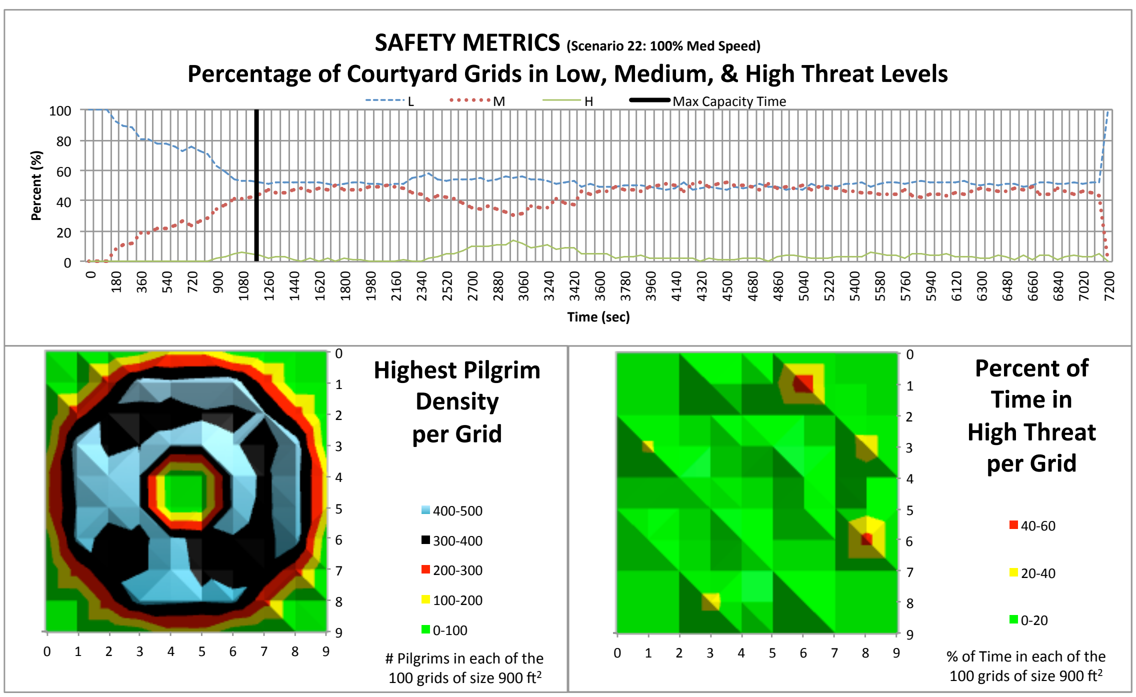


Figure 93: Safety plots for scenario 23

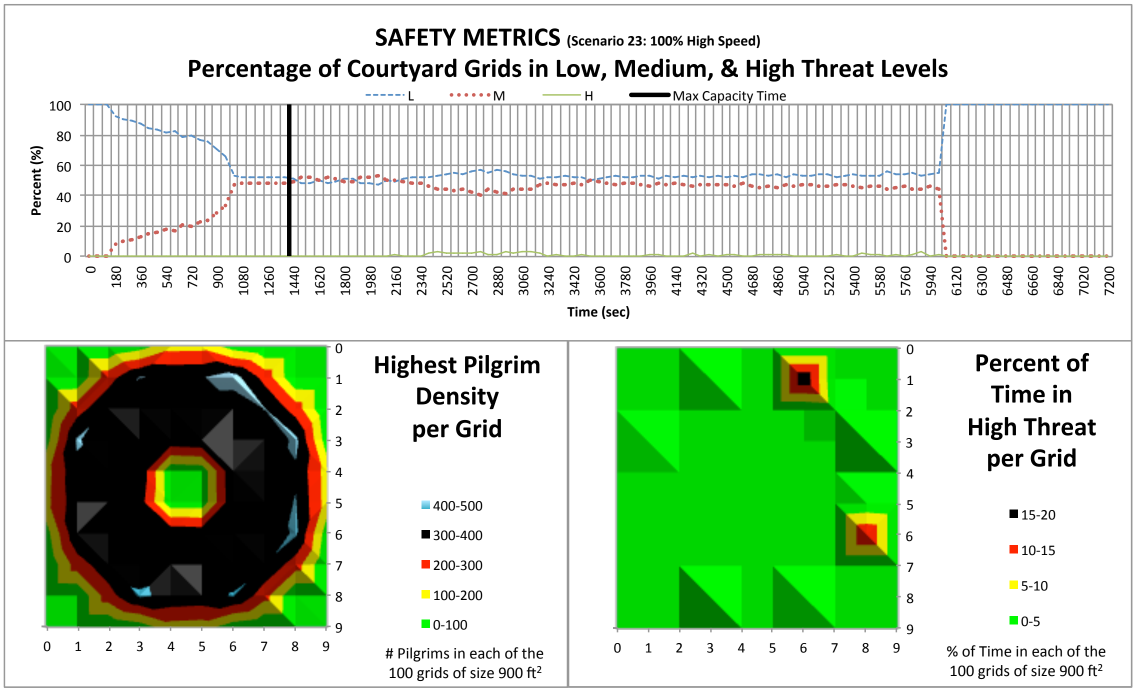


Figure 94: Safety plots for scenario 39

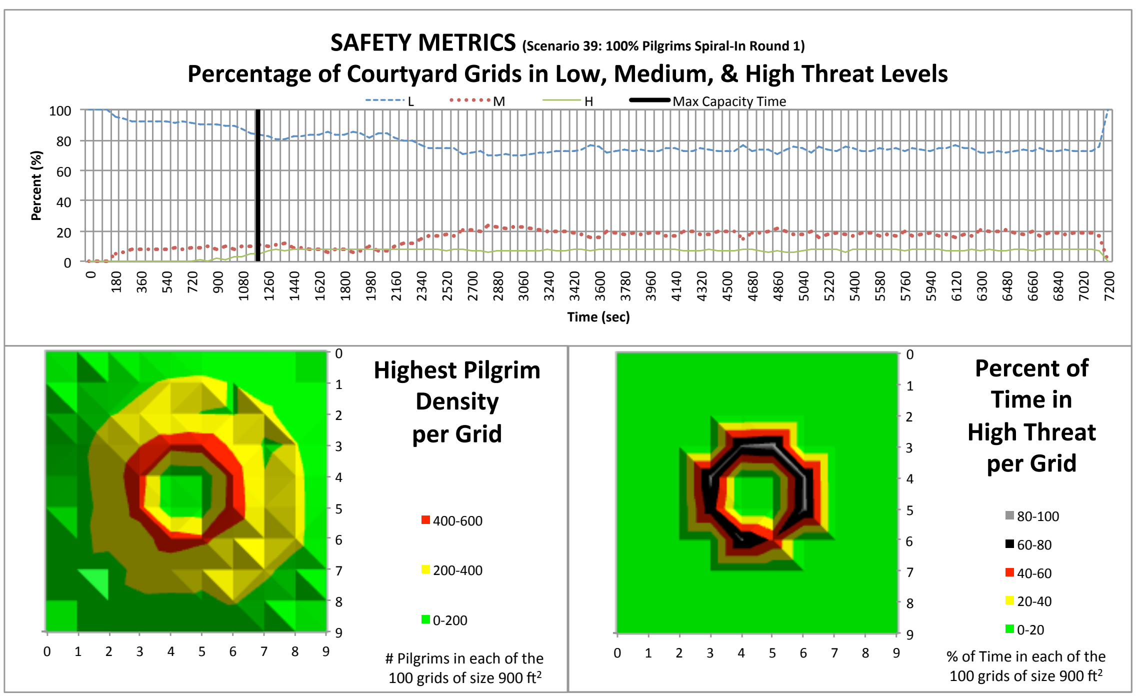


Figure 95: Safety plots for scenario 40

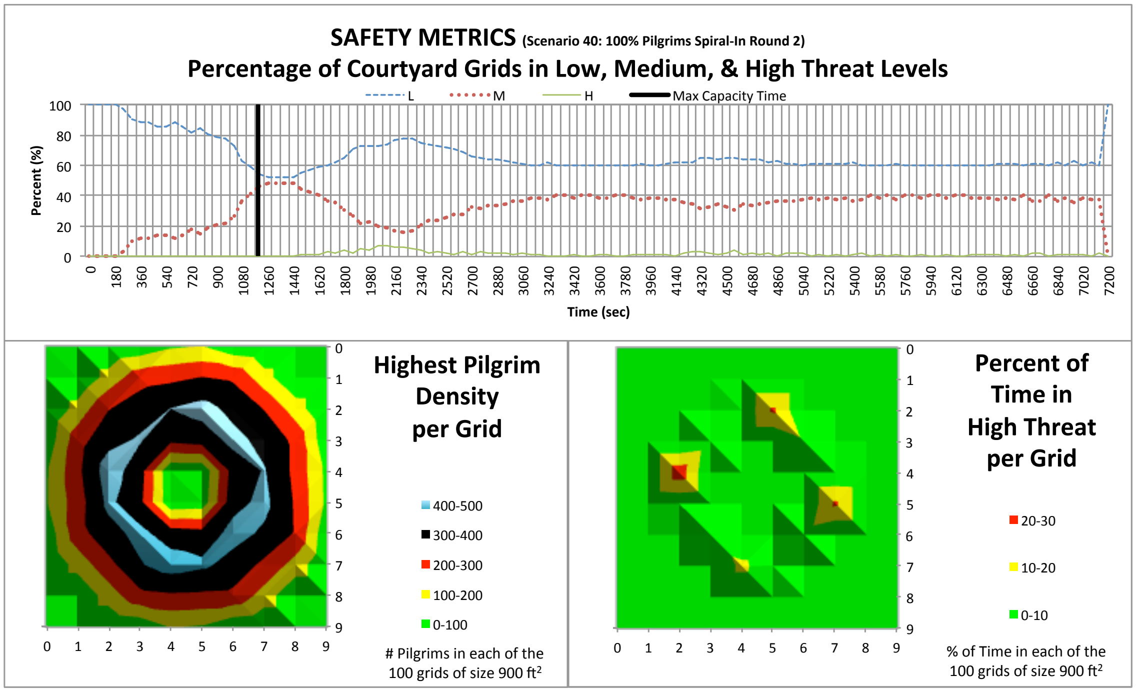


Figure 96: Safety plots for scenario 41

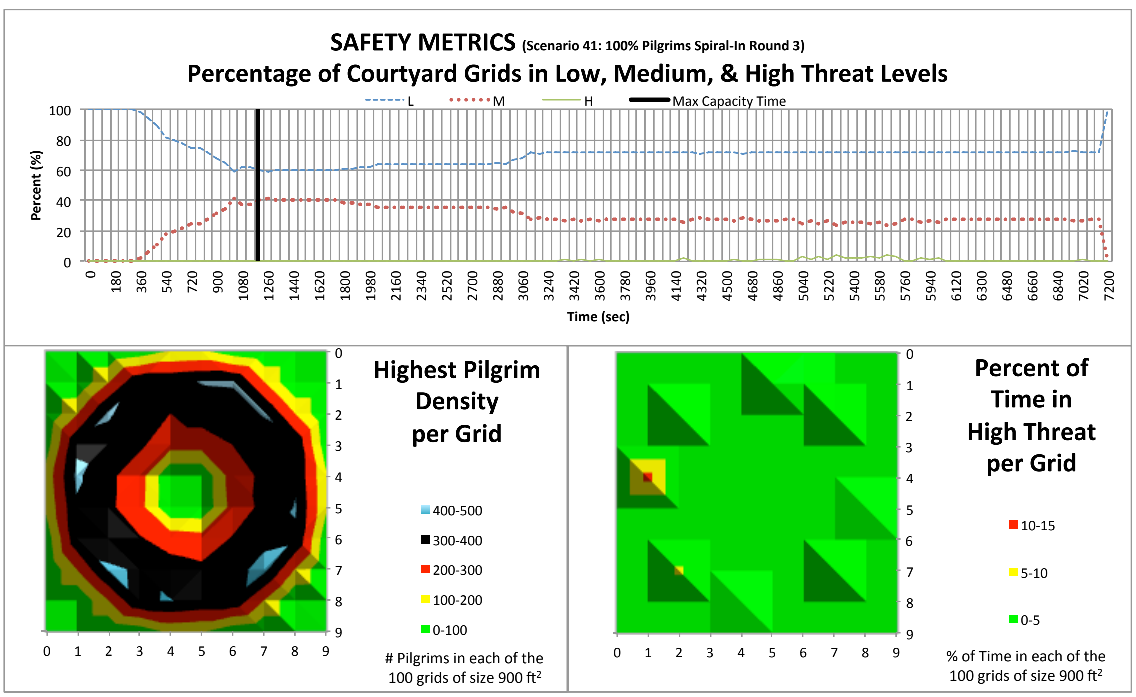


Figure 97: Safety plots for scenario 42