J. Electrical Systems 20-7s (2024): 666-683

[1]Kawther Saeedi
[2]Abdulaziz Abdullah
[3]Marwa Sonbul
[4]Ahmad Hatim Hassan Qadi
[5]Liping Zhao
[6]Kawthar Moria
[7]Sultanah M. Alshammari
[8]Rehab Ashari

Capacity Utilization Assessment Using Discrete-Event Simulation: Case Study of a High-Density Crowd Visiting the Holy Rawda in the City of Madinah

Abstract: - Managing a high-density crowd is challenging, especially when space is limited, due to increased risk of crowd disasters. There are many considerations to lower disaster risk and ensure crowd safety such as infrastructure, facility, staff, emergency response plan, education and awareness. This paper investigates capacity management, which is the most critical consideration when space is limited. Discrete-event simulation (DES) technique is highly adept at reproducing complex real-world operations and can incorporate numerous stochastic variables, thereby improving its effectiveness in decision-making. The objective of this study is to assess capacity utilization of small space through formulating space features and crowd dynamic with a DES model. The model is intended to provide support for informed decision-making process related to capacity management. A real case study about a high-density crowd visiting the Holy Rawda was employed. The data related to the visiting parameters and visit experience KPIs were captured through a range of interviews and actual visits. Comparing the results of the simulation scenarios against the proposed KPIs had a surprising result, there is only 79% utilization of the area, although, intensive high-density crowd were featured during all the visits. It means better management of the crowd may allow 21% more visitors to visit the Holy Rawda.

Keywords: High-Density Crowd, Crowd Safety, Crowd Dynamic, The Holy Rawda, Discrete Event Simulation

1. Introduction

A high-density crowd is a challenging problem that has been addressed in literature from different aspects [1]. Saudi Arabia faces high-density crowd problems, especially at the two holy mosques that Muslims from all over the world visit to perform the Islamic rituals [2]. Due to the importance of these rituals, Vision 2030 sets a specific goal to enable 30 million pilgrims achieve a transformative faith experience [3] through improving their experience of hospitality, space, safety and other services. Crowd management is a complex item on the agenda, espe-

1 [1*,2,6,7,8]Faculty of Computing and Information Technology, King Abdul Aziz University, Jeddah, 21551, Saudi Arabia; [*]Emai: ksaeedi@kau.edu.sa, Tel.: (+966126952000 ext:26157) Emai: maaabdullah@kau.edu.sa, Emai: kmoria@kau.edu.sa, Emai: sshammari@kau.edu.sa, Emai: rashary@kau.edu.sa

[3]King Saud University, Riyadh, 12372, Saudi Arabia; Emai: msonbul@ksu.edu.sa

[4]Linguistics and Translation & Custodian of the Two Holy Mosques Institute - Umm Al-Qura University, Makkah al-Mukarramah 24382, Saudi Arabia;

Emai: ahqadi@uqu.edu.sa

[5]Department of Computer Science, The University of Manchester, Manchester, UK, M13 9PL; Liping.Zhao@manchester.ac.uk

Email: lksaeedi@kau.edu.sa.

cially when space is limited, and the event is time-limited [4]. A prime example is visiting one of the most important sites for pilgrims, the Holy Rawda, between the prophet's house and his prayer area within Prophet Mohammed's (PBUH) Mosque. This space is special as it is next to his grave and is described as a piece of Paradise. The Holy Rawda space is limited to 333.69 m2 and cannot be expanded, both because its dimensions are described precisely in the Islamic text and in order to preserve its respected architectural heritage. The tranquility of this place attracts Muslims to spend longer in prayer, in reading the Holy Quran and in contemplation. However, at the time of writing, especially for female visitors it has been impossible for decades to enjoy its tranquility due to the number of visitors and limited visiting times. In fact, as reported in one interview, it can be stressful and involve collisions, pushing, falling and stampede.

Visits by women to the Holy Rawda are challenging than for men due to the smaller space assigned to them. Only 189.69 m2 of Holy Rawda is made available. There is greater crowd density since visits are restricted to just two or three daily sessions, depending on the season. Moreover, since women use the mosque's north gates and the Holy Rawda is in the south, the site is a long way from the entrance. These additional constraints imposed by the mosque's authority, besides ensuring female privacy and comfort during the visit, are aligned to Islamic commands and historical practices; however, as a result women wait longer, walk farther, and are hurried through the Holy Rawda, resulting in exhaustion and stress that in most cases have disturbed the visitor's tranquility. Despite the extraordinary efforts to manage the crowds at the Holy Rawda, no study relating to the challenges of female visits is found in the scientific literature. This research aims to use simulation to investigate the current visiting dynamics, identify its challenges and propose KPIs to assess the quality of the experience. Simulation is a commonly used approach to studying and analyzing current scenarios [5], [6], [7], [8], [9], as it is a powerful tool for crowding problems [10] to help decision-makers in planning alternative solutions [11]. The work was conducted using simulation as commonly used in similar studies [12], [13], [14]. To understand the visiting dynamic and identify the relevant simulation variables, 30 visits were undertaken by the research team in several Islamic seasons over two years (2019 to 2020).

Additional data were collected from interviews with female crowd agents at the Agency of the General Presidency for the Affairs of the Prophet's Mosque [15] and a convenience sample of (women) visitors' both before and after their visit. Discrete event simulation (DES) [10], [16] was adopted to simulate the scenario of a woman's visit to the Holy Rawda, at the same time providing a graphical user interface to represent her visit's constraints.

The base model of the current visit procedure was developed on a blueprint of the Holy Mosque using ExtendSim tool [17]. An iterative process of build, validate and verify concluded in a model with a 95% confidence rate and 0.001 error rate. The results were compared to seven identified Key Performance Indicators (KPIs) relating to the number of people and waiting times at various stages of the visit, as well as the space utilization of the Holy Rawda.

Comparing the simulation results of the current visiting scenarios against the proposed KPI reveals a surprising result. Despite the crowd density of the visit experience, there is only 79% utilization of capacity: in other words, there is scope to increase capacity by as much as 21% to achieve optimum utilization. The simulation also reveals that the waiting time ranges from 45 minutes to five hours. In the discussion section of this paper, the results are discussed in detail and a possible adjustment is proposed to optimize women's visits to the Holy Rawda.

The paper starts by describing the context of the problem in detail, then gives the background of computer simulation approaches, illustrating the approaches to simulating such problems. Section 4 gives the works related to simulation of Islamic rituals in Saudi Arabia. Section 5 details the simulation methodology, followed by the simulation results and their validation in section 6. Section 7 discusses the study's result, draws conclusion and makes recommendations. Finally, section 8 highlights the limitations of this study.

2. case study context: The problem with women's visits to the Holy Rawda

This section explains the problem context in detail through giving the geography of the Holy Rawda site and the crowd's movements, from entering the mosque to exiting after the visit. To understand the process and the reasoning about the process. Being members of the crowd visiting the Holy Rawda helped the research team to understand its behavior, distribution density, cultural background impact and expectations of waiting time. An additional source of information was a formal interview with the female crowed management leader and observation of the preparations for female visiting time by the crowd management team [15]. This helped to understand the reasoning behind the practices to manage the crowd and the supporting logistics and to estimate the numbers during visiting times. The third source of information was the Custodian of the Two Holy Mosques Institute for Hajj and Umrah Research [18], which provided blueprints of the Holy Mosques and its surroundings as well as brainstorming possible solutions and their limitations.

An geographical characteristics of the Holy Rawda within Prophet Mohammed (PBUH) mosque are shown in Figure 1. The Holy Rawda is a 333.69 m2 area in the southern part of the Holy Mosque between the Prophet Mohammed (PBUH) house where he was buried and his prayer area. This location in the central area of the old building is rich with Islamic heritage and adjacent to other Islamic ritual objects. The Holy Rawda is within the male prayer area. For this reason, women are required to approach from the northern part of the mosque, shown with double arrows, toward the south, then exit on the route shown with single arrows to the north. During women's visits only two-thirds of the area of the Holy Rawda, around 12 by 12 square meters, is allocated for use. As reported by the crowd representative, this area must accommodate about 300 female visitors to pray, estimated by the number of occupied carpets in the waiting area. A temporary partition 2 meters high and 523.35 meters long is erected to separate the prayer area from the route from the female section. Evacuating the area and setting up this partition (the dark dashed line in Figure 1) takes about 35 minutes.

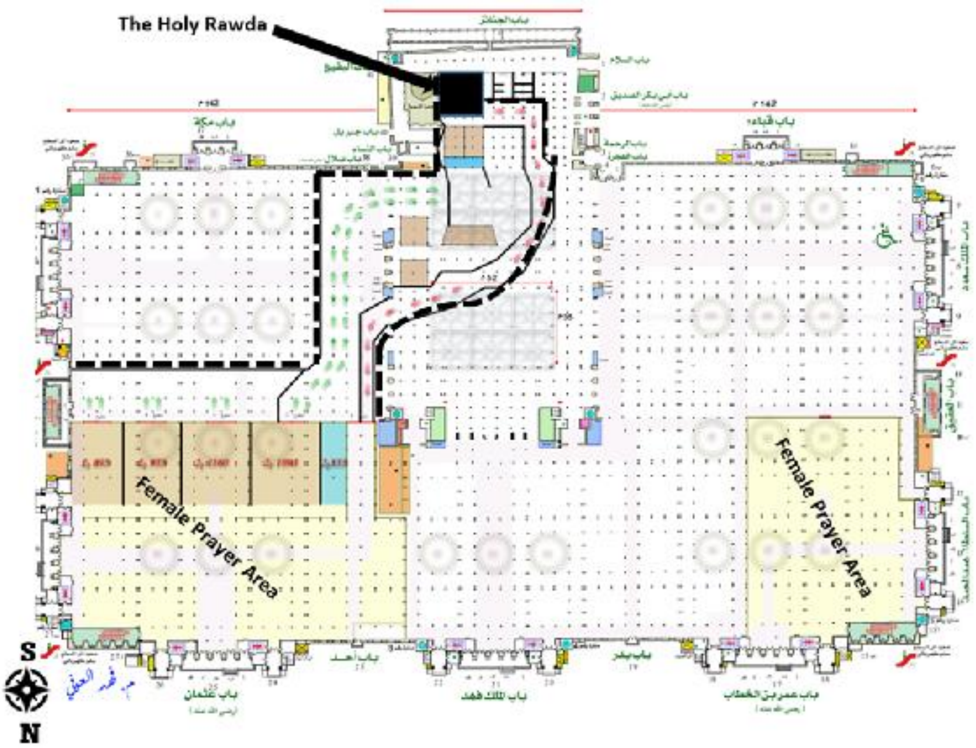


Figure 1. Blueprint for visits arrangement to the Holy Rawda [2].

Depending on the Islamic season, visits to the Holy Rawda by women are possible only two or three times a day: from sunrise until an hour before Dhuhr prayers; after Dhuhr prayers to an hour before Asr prayers; and (3) after Isha prayers until Qyam prayers. Prayer times relate to daylight hours, hence in winter only two visits are available for women as the day is shorter. At each visiting session women visitors are put into groups, each guided by a member of the crowd management team. The number of groups depends on the length of the session, which varies from 2 hours to 5 hours 27 minutes.

Preparing the Holy Rawda for women's visits takes about 35 to 40 minutes and involves evacuating the men's area and installing the partition immediately after prayers. The women's area is to the east, where five waiting areas are sited next to the gates to the Holy Rawda. A section on the west side is dedicated to those in special need. Visitors arrive at the waiting area well before prayer time to get a place in the waiting area before it becomes full.

Around 4,800 visitors wait in these four sections, each holding around 1,200 people. Waiting times to enter the Holy Rawda can be 5 hours, and visitors can become physically exhausted and irritated. When the visit begins, a gate measuring 4.22 meters wide opens for the first batch of 1,200 visitors. The following pattern of visitors from the gate to the Holy Rawda was observed:

Figure 2. Crowd density inside the Holy Rawda. Taken by author's personal camera, 16 May 2019.

Those visitors with limited patience stand next to each other close to the door. They push and run toward the Holy Rawda as soon as the door opens, as shown in Figure 2, resembling the flow of water. The organizers do not attempt to intervene to avoid collisions, stampede, and falls. These visitors normally run to reach the Holy Rawda, then ask to leave after just 10 minutes.

1. The remaining visitors walk patiently to the Holy Rawda. The organizers group them into batches of 300 in the second waiting area (Area 2) to enter the Holy Rawda one at a time. Doing so in a small space at 10- to 12-minute intervals is a challenge. Since the visitors enter the Holy Rawda in groups of 300, another stampede arises when clearing the area of each cohort in the tight slot of 10 to 15 minutes. This disrupts the spiritual experience. Figure 3 is a photograph of the situation.

Figure 3. Crowd density in waiting area. Taken by author's personal camera, 25 March 2019.

Illustrating the context of a visit to the Holy Rawda is important to understand the challenges that the authorities face to control the mass of visitors. Alongside the extraordinary efforts made to manage this complex and challenging problem, representation using simulation tools helps to see the problem from a new angle, understand it better and appreciate its variables. This supports decision-makers in crowd management. It is important to note that the problem is studied without proposing any change to the construction of the mosque or the policies concerning visits, which are outside the scope of this research.

3. Computer Simulation Techniques

Computer simulation is defined as the exemplification of the dynamic characteristics of real-world elements through specific digital models using computer technology [19], [20]. The model is constrained to achieve predictive knowledge valuable to decision-making on aspects of the entire real system. Therefore, a simulation model is frequently used when high-risk decisions must be taken, the consequences of which are not directly visible, or no suitable analytical solutions are available [21]. Since most dynamic issues in practice cannot be performed and solved fully by mathematical equations, computer simulation is a powerful and flexible method in complex system analysis [10].

The goal of simulation can vary from identifying bottlenecks to streamlining activities. The simulation itself does not present an immediate solution; it is to understand the behavior of the system. So, when a behavior is known, it is possible to undertake improvements and effective interventions to the system. The simulation subsequently confirms whether the entire system is to react similarly to the simulation. The compliance of the whole system with the simulated one relies on its quality and accuracy [22], [23].

Simulation systems are categorized by their characteristics [10]: branching into deterministic or stochastic, static, or dynamic, then discrete or continuous. Deterministic simulation models include no random variables and have a recognized set of inputs, which will result in a unique collection of outputs. On the other hand, stochastic simulation models have one or more random variables as inputs. Random inputs lead to random outputs. As shown in Figure 4, the deterministic and the stochastic models can be either static or Discrete-Event Simulation (DES), which is the process of collecting well-defined events from the behavior of a complex system sequentially [24], with change in the system state at a specific time and cause [25].

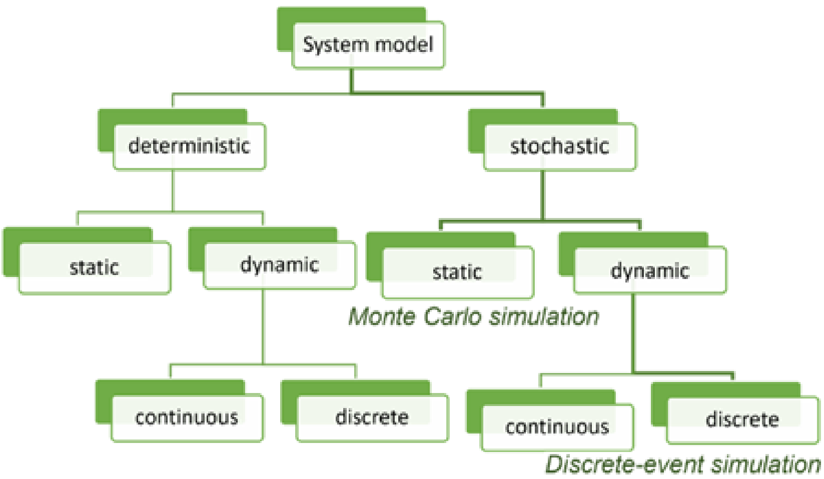


Figure 4. Classification of simulation models [1].

This type of simulation is used in several real-life situations, such as healthcare [24], [25], [26], transportation and wireless networks [27]. To use DES effectively, some essential characteristics should be predefined, such as starting and ending points, the method of monitoring the elapsed time from starting the process, discrete events that have occurred from the beginning of the process and discrete events expected or pending. Moreover, DES involves a combination of elements (people, procedures, materials, equipment, information, space, and energy) together with system resources (equipment, tools and personnel) [24]. Each process is a series of logically related activities of different duration, undertaken to achieve a specified outcome. Activities involve the use of process elements and resources. The item library simulates those systems using blocks to mimic operations and timings that represent the actual occurrence of events [28].

4. Work related to simulating Islamic mass gatherings

The two Holy Mosques attract millions of Muslims on a daily basis, especially during Ramadan and Hajj. Around 3 million visitors come from all over the world to perform the Hajj Rituals [29]. Visiting Prophet Mohammed (PBUH) mosque during Hajj is not mandatory; however, for convenience, most visitors from other countries visit Prophet Mohammed (PBUH) mosque on the same trip. Compared to research on crowds in the Hajj and Umrah context, less has been conducted on the crowds for Prophet Mohammed (PBUH) mosque. To the best of our knowledge, there is no work on the female crowds visiting the Holy Rawda. Therefore, this section highlights studies on Islamic rituals in Saudi Arabia, as this deals with similar crowds that are governed by the same authorities.

A comprehensive survey on the technology used for Hajj crowd management research from 2007 to 2020 [29] shows a taxonomy of their design to implement solutions that facilitate crowd management during Hajj. It shows that crowd modelling and simulation is the main tool used for planning and managing the event. Simulation is used to study pilgrims' movement during Hajj rituals [30], [31], [32], [33], [34], [35], [36], [37], [38], [39], [40], [41], [42], [43], [44], [45], to study pilgrims during Tawaf ritual [46], [47], [48], [49] and to plan utility and services [50] and traffic flow [51], [52], [53], [54]. Furthermore, there are range of studies adopt simulation of hajj data in different prediction model such as disease spread during hajj [55] and possible energy source form food waste during hajj [56].

The movement of pilgrims in the Tawaf was simulated by DES, aiming to increase throughput and enhance pilgrims' experience [47]. The parameters of the model include the size of the Tawaf circle, the number of pilgrims, density, velocity, time, capacity, distance, and speed. Two separate cellular automated models simulate circular movements and free steps from source to destination using the statistical discrete event approach.

A recent study explored a similar issue in terms of location and density, analyzing the crowd dynamics of visitors to the Prophet's (PBUH) grave for the Ziara ritual [5]. People undertaking the Ziara ritual pass along a straight corridor in one direction from Alsalam gate in the west towards Gate in the east. Walking speed is calculated from video observation at 1.2 meter per second, with a standard deviation of 0.30 meter per second, but slows to 0.42 meter per second in front of the grave, with a standard deviation of 0.2 meter per second [5]. To simulate the crowd, Mass Motion was used with various parameter settings. The study indicated a break down in the conditions when the flow of people exceeds 9,200 persons/hour in front of the grave and proposed the introduction queueing outside Alsalam gate. Although this work is the most relevant to this current study, the Ziara ritual only allows male visitors and has no time restrictions. Visiting the Holy Rawda as a woman involves restricted visiting time, a longer distance from the gates and a stop-go motion of the crowds, since for women, for reasons of privacy, there has to be prior evacuation of males and restrictions on taking videos.

Of the limited studies related to visiting the Prophet Mohammed's (PBUH) mosques, two analyze the crowd characteristics in Al-Masjed Al-Nabawi [57], [58]. Both used computer vision and simulation to represent crowds and proposed alternative systems to develop indicators to support decision-makers. The first studied the crowds at the Holy Rawda of Al-Masjed Al-Nabawi, where they exhibit low interpersonal distance and there is a corresponding loss of individual freedom of movement [57]. This study uses various simulation models and computer vision to enable direct attainment of statistics and indicators. The second studied the heavily congested conditions at busy times of day using data collected during Ramadan and Dhul-Hijjah to examine safety aspects, recommending future solutions [58]. Conventional manual head-counting was adopted to determine the actual numbers from the videos and photos captured by the Al-Haram authorities. The analyses show that the crowd dynamics in Ramadan are statistically different from those at all other times, which are practically identical.

In a further related work, the maximum crowd density of visitors to the Prophet Mohammed's (PBUH) grave was predicted by simulation [59]. The simulation of crowd movements from the grave to exit gate inside the holy mosque used a tool called Mass Motion [60]. The study proposed grouping people into batches of various sizes for different sessions. Although this study is close to the context of the Holy Rawda, again it focuses on the Ziara ritual, which is for men only and thus completely segregated from the female visitors.

The evacuation plan at the Prophet Mohammed's (PBUH) mosque has been studied through comparing simulation tools [61]. Those recommended for simulation are Exodus [62], Simwalk [63] and two open-source tools, STEPS [64] and FDS+EVAC [65]. The variables in the simulations are the floorplan, the total occupancy of the mosque and the movement speed of pilgrims. Evacuation time is analyzed, being the most critical variable in an emergency. To study the evacuation the research recommends seven zones at the Prophet Mohammed (PBUH) mosque. Although this is one of few studies to consider female zones inside a mosque, it does not address evacuation procedures at visiting times for women.

5. Simulation Methodology

The current study conducted following the basic simulation methodology, as commonly used in similar research [12], [13], [14]. We extended the methodology with additional steps, as shown in Figure 5.

- **Step 1**: Understand the context of the simulation by scoping the problem, its variables, and surrounding conditions. Section 2 describes women's visits to the Holy Rawda, the visiting constraints, and the frame of the visit.

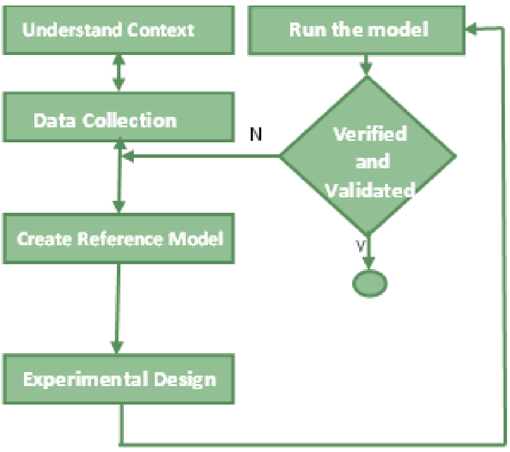


Figure 5. Simulation methodology

- **Step 2:** Data collection of simulation input parameters. Observations and interviews were the source of the simulation data, and 30 visits were performed in 2019 and 2020 to experience various visiting times and seasons. This helped to develop several scenarios with dissimilar timestamping. The multiple interviews with crowd management personnel at the Holy Mosque greatly helped to critically understand the process of women's visits and the preparations involved. Through the interview researchers captured important data related to the sessions, the number of visitors and the process. The data collected in this step were used to build the simulation reference model at Step 3 in the simulation methodology.

- **Step 3:** The descriptive modeling step for building a reference model that is a rigorous, systematic analysis of a model's relevance and consistency with observed behavior and data to ensure that it is fit for purpose [66]. The process of female visiting the Holy Rawda can be divided into three areas, as in Figure 6, each with distinct attributes and a specific capacity.

Waiting Area 1: 2,880 m^2 on the west side of the female part of the mosque. To control the crowd, this area is divided into four (A, B, C, D), each holding 1,200 visitors. Immediately after prayers, the zone around the Holy Rawda is prepared for women visitors. It takes 35 to 40 minutes to clear it and install the partitions. All 1,200 visitors are asked to move to Waiting Area 2 once the gate from one of the four areas opens, and it takes up to 3 minutes to empty the space and close the gate. Therefore, the minimum waiting time is 35 minutes; the longest waiting time observed in high season is 5 hours.

Waiting Area 2: To control the entrance to the limited space of the Holy Rawda, the visitors are split into four smaller groups of 300 in this area, as estimated by the number of occupied carpets. The first group enters the holy area immediately and subsequent groups wait 15 minutes for the previous one to exit.

The Holy Rawda: The destination for thousands of visitors to pray, and here they need space to stand, bow and kneel comfortably for a few minutes. The space assigned for women is 189.96 m^2. The space fits 300 comfortably, but usually must take 365 to 400. The area for each person is 0.6 m^2, equivalent to a standard prayer mat. After 12 minutes each group is asked to leave the Holy Rawda by way of the exit. It was observed that not everyone follows this exit plan, thus it is not possible to empty the Holy Rawda completely for the next group. Once the final group in Waiting Area 2 has entered the Holy Rawda, the gate into Waiting Area 1 opens for the next round of visitors.

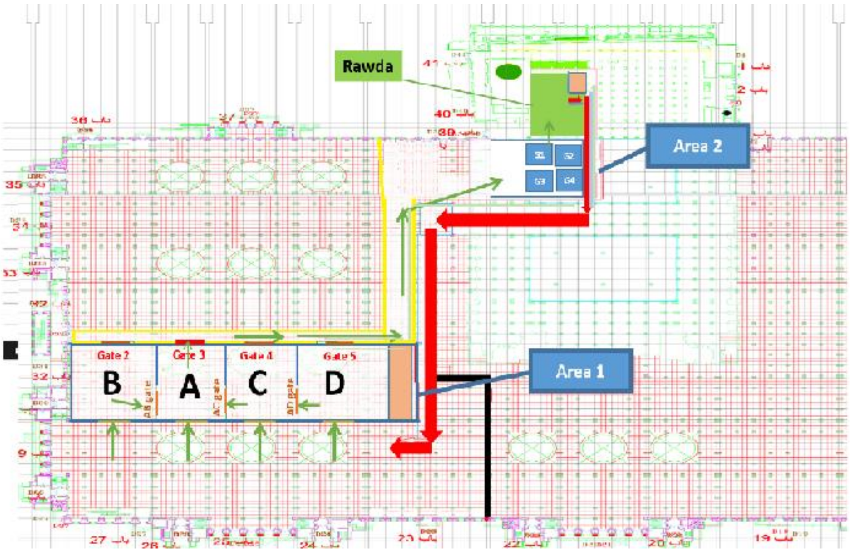


Figure 6: Reference model for woman's visit.

- **Step 4:** The experimental design consisted of configuring a digital version of the logic defined in the reference model to a build simulation base model [67]. This stage started by setting the input parameters with a proper distribution, then, designing the experimental base model using ExtendSim software blocks, as in Figure 7. The simulation logic is in four parts to reflect visitors' activities in each of the visiting areas depicted in the reference model: arrival; proceeding to Waiting Area 2; proceeding to the Holy Rawda area; and at the Holy Rawda itself. The following section illustrates this logic.

Input parameters and data distribution

The input parameters consist of three attributes. The first is the parameter name, which comprises the waiting area number and Rawda capacity: 1,200 was taken as the capacity of each wating area. The second is the parameter's value of 0 or 1 to indicate whether the gate is open or closed, and 300 was set for the Rawda's normal capacity, with 400 at maximum capacity. The parameters to run the simulation are given in Table 1. The third attribute is batch size, giving visitor numbers for each area.

	Parameter Name[1]	Parameter Value[2]	BatchSize[3]
1	Area A initial demand	1.00	1200
2	Area B initial demand	0.00	1200
3	Area C initial demand	0.00	1200
4	Area D initial demand	0.00	1200
5	Area X initial demand	0.00	0
6	G1	1.00	300
7	G2	0.00	300
8	G3	0.00	300
9	G4	0.00	300
10	G5	0.00	0
11	Rawda Capacity Normal	300.00	0
12	Rawda Max Capacity	400.00	0

Table 1. Simulation input parameters

The best-fit distribution corresponding the collected data for processing time at the Holy Rawda is the empirical discrete distribution [68], which is appropriate for this study's data set. This distribution represents visitors entering the Rawda, according to the data: 45% of visitors spent 12 minutes; 20% spent 30 minutes; 20% spent 7 minutes; and 15% spent 45 minutes. Maximum capacity was set at 400 and the delay to 45 minutes, being the maximum that visitors spend there. The aim of this study is to create a management model to reduce delays at the Holy Rawda using the current distribution, which could improve the crowd management and enhance the visitors' experience.

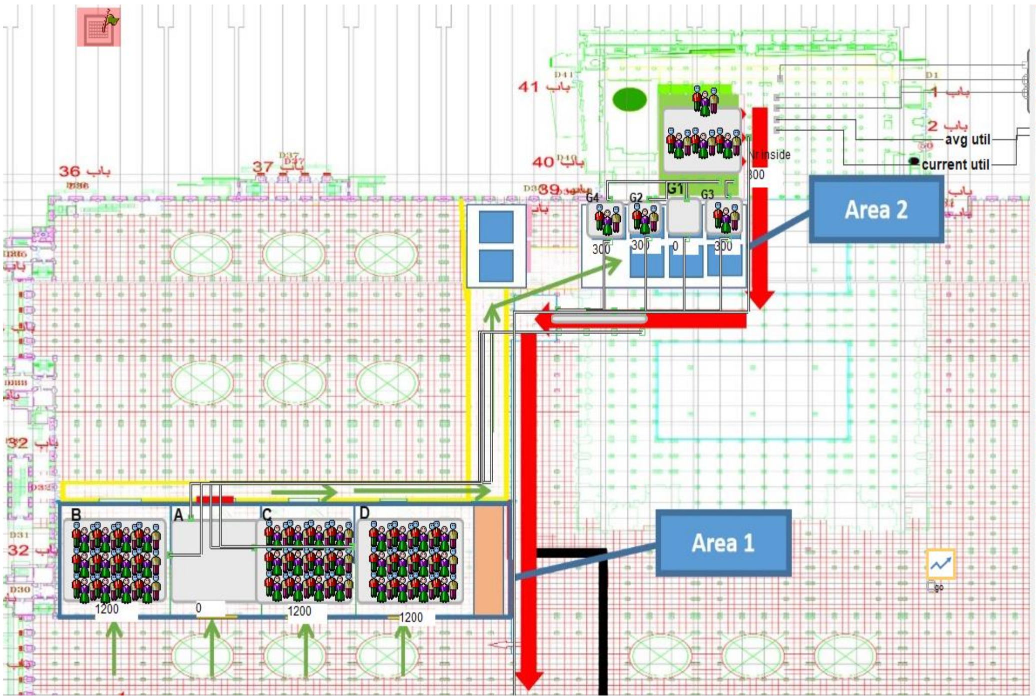


Figure 7: Running the simulated base model.

Designing the experimental base model

1-Simulate the Arrival:

• The arrival of the female visitors to the first waiting areas, A, B, C and D, is represented as entities in the ExtendSim simulator. As shown in Figure 7-A, several blocks of the simulator were used to simulate the arrival process, such as queue and activity blocks, showing a delay of 35 minutes in opening the Area 1 gates to start a visit. Also, a gate block is used to control the flow of entities to the next area, by reading values from the database. If the value is 1, it passes the entities, otherwise it waits until it equals 1.

2-Simulate Visitors Proceeding to the Area 2:

Once the entities pass through Areas A, B, C or D, they reach Area 2 in just 3 minutes. This used the select and activity blocks, as in Figure 7-B.

3-Simulate Visitors Proceeding to the Holy Rawda:

The distributed entities in Area 2 were collected in the batch block once again, as in Figure 7 -C. The gate block reads the values from the database and, if it equals 1, the batched entity moves to the equation block, which once again closes the gate by writing zero to the system parameter to control the logic for this gate.

4-At Holy Rawda Area:

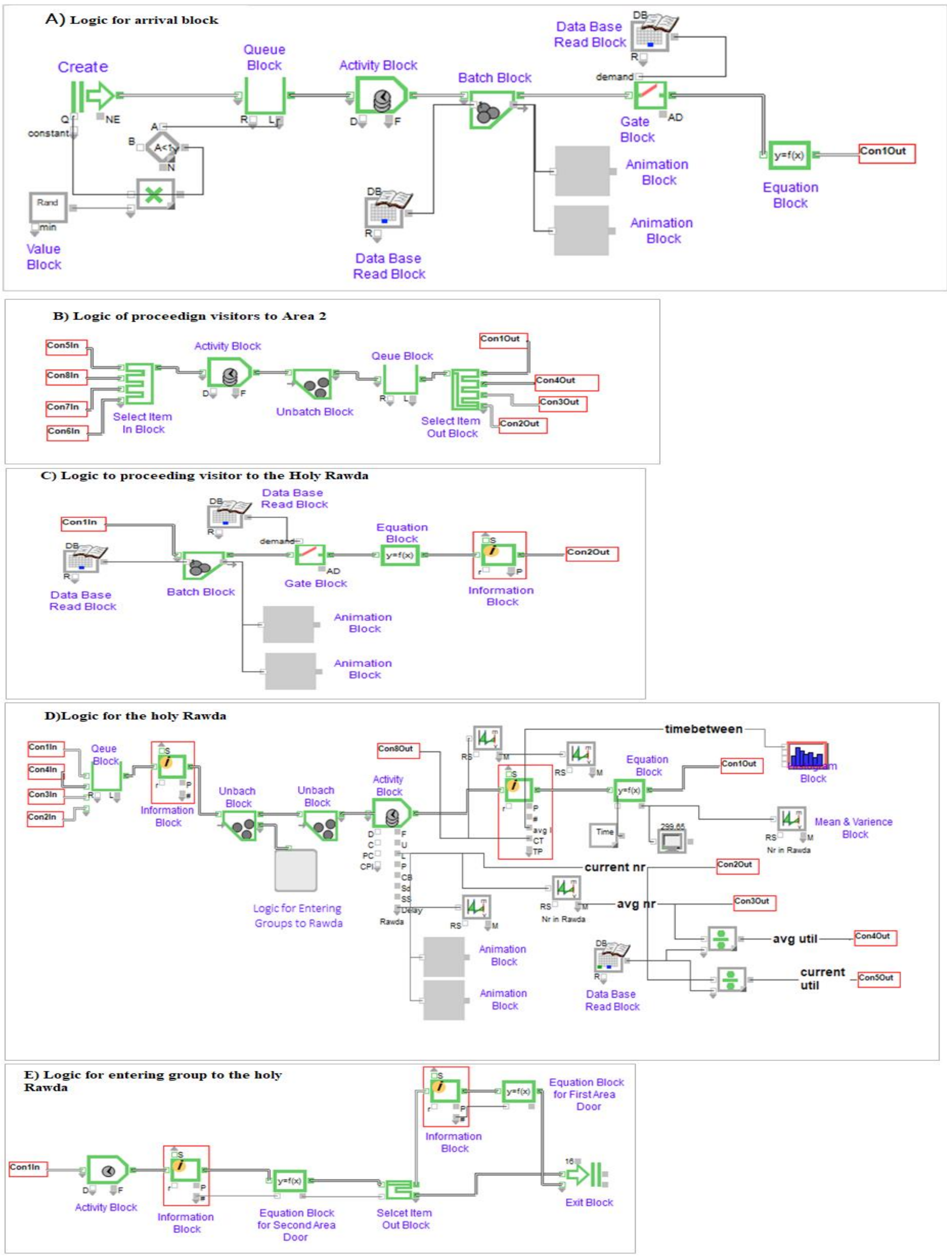


Figure 8: Experimental design of the simulated base model

The entities arriving from each waiting area are connected to a queue block, then to an information block that counts the items passing through, as in Figure 7-D. Then, two Un-batch blocks are used, the first one to open the gate of the next waiting group after 14 minutes, and the second to Un-batch the items, which represents visitors arriving from one of the waiting groups. The first Un-batch block is connected to another block that contains the logic for admitting the groups one after another to the Holy Rawda, as in Figure 7-E.

• **Step 5:** The simulation was run with the current visit variables. It ran for 300 minutes, representing the longest visiting period at the Holy Rawda. A snapshot of the simulation is shown in Figure. 8. The run was performed 33 times, as both the error and the confidence values reached a static value by the thirtieth iteration, at 0.001 with a 95% confidence interval.

Step 4: Verification and validation represent the sixth step and ensure that the developed model reflects the re-al-life scenario in terms of behavior and results. Verification and validation are connected. Verification happens first, to ensure that the model is correctly built [69], then validation concerns whether if it is the right model.

Verification is defined as checking that a model's implementation and its associated data indeed express the developer's conceptual specification and description [70].

To verify the simulated base model, five KPIs were identified to analyze the results, identified from the capacity and time of each visiting area process, including the average Rawda visitors in each area per unit time, their average waiting time, the total number of visitors served, the utilization of the Rawda area and, finally, the average minimum/maximum total visit time. A detailed illustration of the simulation results and its validation is given in section 6.

6. Results and Validation

This section describes the run results of the simulation and validates its output against the five identified KPIs, based on two key factors: the capacity and time, the main indicators of utilization of the Holy Rawda. Capacity refers to the visitors in the various areas during each visit. Time refers to how many minutes these visitors spend in each area. Tracking capacity and time in each area helped to calculate the utilization and the time to undertake the visit. Below is a discussion and analysis of each of these KPIs, based on the results of the simulation.

KPI 1: Total Number of Visitors Served: This represents the overall numbers in a visiting session. The running results show 4,800 entering Waiting Area 1 and exiting the Holy Rawda at the end of the session. This is equal to the estimated number, divided into 1,200 visitors in Waiting Areas A, B, C and D.

KPI 2: Average Number of Visitors in The Holy Rawda Area per Unit of Time: This represents the average number in each group visiting the Holy Rawda. The capacity is 300, and 400 at peak times. The running results from the base model show that the average number inside the Holy Rawda is 300 and represented by Equation (1).

$$AverageNumberOfVisitors = \frac{Total\ number\ of\ all\ visitors}{Rawda\ Capacity} \quad (1)$$

The plotter chart in Figure 9 depicts the variance between the current number of visitors and the average in the Holy Rawda. The first 38 minutes is 0, meaning that the Holy Rawda is empty at that time, when setting up the partition and preparing to receive visitors. So, even though there is overcrowding in the Holy Rawda area, it is underutilized for a short time. Then the number of visitors climbs to 300, representing the first group, then drops to 250, then to 100, which shows that visitors are exiting the Holy Rawda at several points in time. When there are still 100 visitors in the Holy Rawda, the second group of 300 visitors enters, which is shown by the blue line climbing to 400. At the 280th minute, the blue line drops, representing the start of preparations to empty the Holy Rawda. As a result, the average number of visitors, shown

by the red line, increases from 50 to 300.

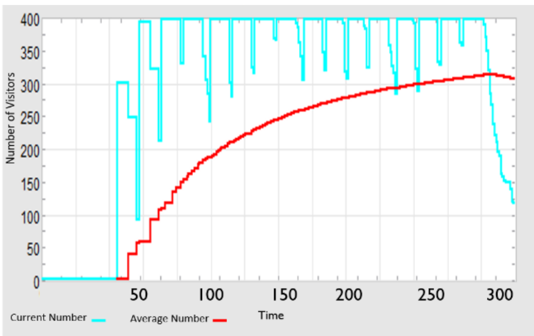


Figure 9: Current number of visitors vs time in the Holy Rawda in simulated base model.

KPI 3: Average Waiting Time of Visitors: This represents the average wait by a visitor before entering the Holy Rawda. The running results are given in Equation (2). It seems to be very long, with an average of 148.15 minutes, which is 2.47 hours.

$$AverageWaitingTime = Average\ waiting\ time\ of\ Area1 + 3\ minutes + Average\ waiting\ time\ of\ Area2 \quad (2)$$

KPI 4: Average Minimum, Maximum, Total Visit Time: These three numbers represent the time from entering a waiting area to exiting the Holy Rawda. The minimum represents the best scenario and the maximum the worst. The average total visit time is 175.23 minutes, or almost 3 hours, given by Equation (3).

$$AverageTotalVisitTime = Average\ waiting\ time + Aaverage\ time\ spent\ in\ Rawda \quad (3)$$

The average minimum spent time in the Holy Rawda is 45 minutes, as shown in the running result represented in Equation (4).

$$AverageMinimumVisitTime = Average\ minimum\ waiting\ time\ spent\ in\ Area1 + 3\ minuts + Average\ minimum\ waiting\ time\ spent\ in\ Area2 + Aaverage\ minimum\ time\ spent\ in\ Rawda \quad (4)$$

The average minimum waiting time in Waiting Area 1 represents the average shortest duration in Waiting Area 1, from admitting visitors until they exit. The 3 minutes is how long it takes to transfer the visitors from Waiting Area 1 to Waiting Area 2. The average minimum waiting time in Area 2 represents the average shortest duration in Waiting Area 2, from entering to exiting to the Holy Rawda. The average minimum time spent in Rawda represents the average shortest duration that the visitors spend in the Holy Rawda, from entering it until they exit.

The average maximum time is 299 minutes, or almost 5 hours, achieved by running the simulated base model represented in Equation (5).

$$AverageMaximumVisitTime = Average\ maximum\ waiting\ time\ spent\ in\ Area1 + 3\ minuts + Average\ maximum\ waiting\ time\ spent\ in\ Area2 + Aaverage\ maximum\ time\ spent\ in\ Rawda \quad (5)$$

The average maximum waiting time in Waiting Area 1 represents the average longest duration time spent in the Waiting Area 1 starting from entering the visitors to this area until they exit from it. The 3 minutes represents the time of transferring the visitors from Area 1 to Area 2. The average maximum waiting time spent in Area 2 represents the average of the highest duration time spending in the Area 2 once the visitors enter this area until they exit from it. The average maximum time spent in Rawda represents the average of the longest duration that visitors spend in the Holy Rawda from entering until exiting.

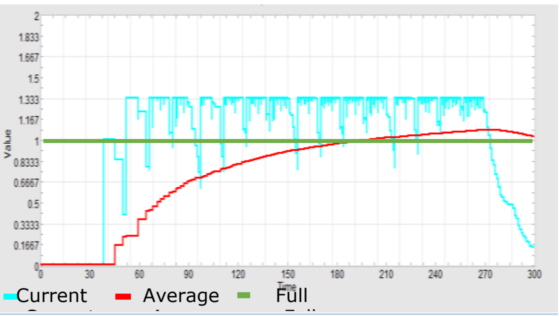


Figure 10: Current and average utilization of the Holy Rawda for simulated base model.

KPI 5: Utilization of the Rawda Area: This KPI depicts the percentage utilization of the Holy Rawda. Holy Rawda utilization is defined as the average time during which it has less than 300 visitors. It was observed during research visits and in interviews that the Holy Rawda is overcrowded all the time, with more than 300 visitors. However, the average utilization value is the average length of time divided by the normal Holy Rawda capacity (300). Therefore, utilization averages 79%, which means that the Holy Rawda sometimes has 300 visitors or more on average when running the model, represented in the plot in Figure 10. However, despite overcrowding in this area, it is underutilized at certain times, with average of 21%. This happens immediately before admitting the second, third and fourth groups of 300 into the Holy Rawda.

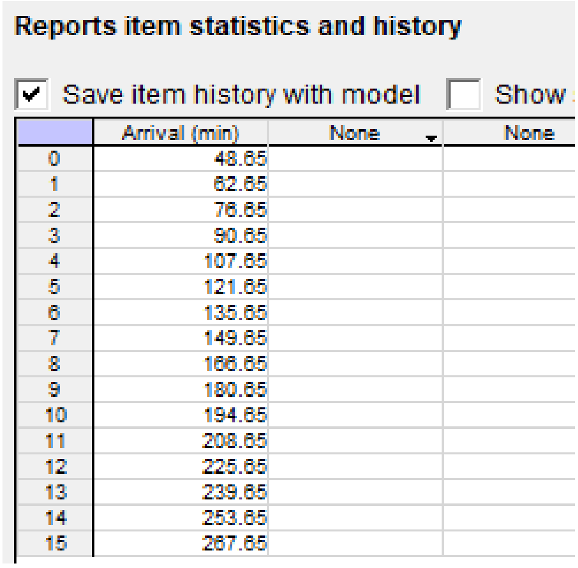
To verify the simulated base model, its running results were compared to the data collected from the organizers, as in Table 2. The second column represents the results of the base model. The third column 'As Is' representing the value of each KPI taken from the collected data. Finally, 'Error' represents the error percentage of the model. To calculate the error, Equation (6) is used.

$$Error\ Percentage = \frac{KPIs'\,Results\,(Simulated\ \ Base\ Model) - KPIs'\,Results\,(As\ Is)}{KPIs'\,Results\ (As\ Is)} * 100 \quad (6)$$

Table 1: Verification results

KPI	Base Model	As is	Error
Total number of visitors served	4,800	4,800	0 %
Average number of visitors in Rawda area per unit time	300	300	0 %
Average waiting time of visitors	148.15 m	150 m	-1.23 %
Average minimum visit time	45 m	45 m	0%
Average maximum visit time	299 m	300 m	-0.33%
Total visit time	175.23 m	180 m	-2.65 %
Utilization of the Rawda area	79%	79%	0 %

Generally, the verification results show that most errors equal 0, which tells us that the simulated base model is verified. For the validity of the simulated base model, some objects like information and history blocks from the item library in ExtendSim were used to see if the simulated base model works according to codes and parameter values that were input, matching the behavior of the reference model as well as the real-life system. As seen in Figure 11 the first group enters the Holy Rawda at 48.65 minutes and then at 62.65, 76.65, 90.65 minutes, and so on, every 14 minutes. This means that the 14-minute logic works correctly to admit each group to the Holy Rawda, and this indicates that the simulated base model is validated.



	Arrival (min)	None	None
0	48.65		
1	62.65		
2	76.65		
3	90.65		
4	107.65		
5	121.65		
6	135.65		
7	149.65		
8	166.65		
9	180.65		
10	194.65		
11	208.65		
12	225.65		
13	239.65		
14	253.65		
15	267.65		

Figure 1: Content of history block for batched items entering the Holy Rawda in simulated base model.

7. Study Limitations

This paper demonstrates the dynamics of women's visits to the Holy Rawda. The study data were captured through observations and interviews, and 30 visits were undertaken throughout 2019 and 2020 by the research team at various times and seasons. Due to COVID-19, all holy rituals were suspended, completely changing the dynamics of performing the Islamic rituals. This involved the imposition of health and safety measures such as social distancing, disinfection, health checks and limits on visitor numbers. This caused dramatic changes to the dynamics described in this paper. The research team consequently faced uncertainty and delayed presenting this work, as there was no information on how the visit dynamics would be after the pandemic. One argument supporting the position of this paper is that depicting previous visiting dynamics using simulation may provide insights for decision-makers when planning the return to full operation after the pandemic.

Another limitation relating to the mechanics of capturing data on the dynamics of women's visits was the impossibility of using video or photography to count visitors. This is due to the respect for female privacy in Islam, known as Hijab. All numbers received from interviewing the agents are estimates with a margin of error, so during the observation visits the research team counted people in each area by manual head count and estimating the people by the number of carpets. Then a fitting equation and averaging were used, as well as adjustment of some values in different iterations of the simulation model.

Another limitation is the exclusion from the simulation of people with special needs and the emergency evacuation scenarios. This was intentional, to focus on the current dynamic and utilization of the Holy Rawda. Inclusion of special needs and emergency evacuation will be the topic of future study.

It is important to highlight that this study investigated only the dynamics of visiting the Holy Rawda, measuring the utilization and duration of the visit. It did not include social or behavioral aspects that influence the visiting dynamics and the spiritual experience. Future studies will analyze the data captured from the interviews to enhance the spiritual experience of visiting the Holy Rawda.

7. Study Limitations

Visiting the Holy Rawda is a challenge for women due to constraints including space, crowd density, limited visiting sessions and the long distance from the gates assigned to women. These are in alignment with Islamic commands, historical practices and the assurance of female privacy and comfort during the visit. Despite the extraordinary efforts made by the authorities to manage the crowd, women struggle to complete the visit (as reported in interviews and observed on visits) because of the dense crowds, long waits, the long distance to walk and being rushed to access and leave. Although this issue was the case for a decade prior to the COVID-19 lockdown, at the time of writing this paper no work found in the scientific literature has studied the female crowd problem. Therefore, this paper offers a unique contribution to literature, demonstrating crowd dynamics with a visual illustration, using simulation, of women's visits to the Holy Rawda.

The simulation was built according to the commonly used methodology to guide the formulation of the problem and validate the results. The data were collected through observation visits and interviews with crowd agents and random visitors. An iterative approach was used to build the base model to demonstrate the learning from the data and observations. DES was used to visualize the visiting dynamics on a blueprint of the Holy Mosque of Madinah. DES was chosen as it is suitable for crowd behaviour, which features stop-start motion. As in the real scenario, the visiting dynamics is divided into three areas: two waiting areas and the Holy Rawda itself. The simulation logic performed a learning curve of 30 runs to reach the static confidence and error rate at 95% and 0.001. Training stopped at 33 runs as no further improvement in the result was recorded. These values are high for this type of scenario, which deals with agent movement motion in a safe environment.

The number of visitors and time to perform the visits were captured in five KPIs, to measure the number of visitors and the time to perform the visit. These were used to calculate the utilization of the Holy Rawda. The simulation results were verified against variables captured from the real-life scenario. The error rate, confidence interval in addition to the KPIs comparison are the three measures that confirm the compatibility of the simulation-based model to the real-life scenario.

An important outcome of this work is the identified KPIs, especially the utilization of the Holy Rawda, as demand is always increasing. The simulation shows only 79% utilization of the Holy Rawda. This figure is surprising, especially when compared to the norm in a real-life visit, as shown in Figure 3. Analyzing the curve in Figure 11 shows that the under-utilization lies in the entry and exit of each group. This was confirmed by the observation visits, revealing that visitors do not follow the exit instruction and that the next group enters before the area is empty. This causes delay and disruption to the crowd flow as well as reducing the utilization. It means that there is room to improve utilization to the optimum and allow 21% more visitors to visit The Holy Rawda.

Another valuable outcome is the finding of the long waiting times that visitors may experience in comparison to the 10 to 12 minutes allowed inside The Holy Rawda. The visit takes 45 minutes at best, and in the worst scenario last up to 5 hours. The simulation shows that it is the women in Waiting Area 1, Group D, who face this long wait. Actual visits confirm this finding, especially in the long visiting session between Ishaa prayers and Qaim and in peak season, as Waiting Area 1 is already full before prayer time. It was also observed and reported in interviews that the long wait causes exhaustion, frustration and stress to visitors and spoils the spiritual experience.

Although this paper does not attempt to provide solutions, the work concludes with recommendations based on its observation of Holy Rawda visits and discussion with various stakeholders. It is difficult to control the movement of a group of 300 in such a limited space and time, therefore when studying potential solutions, the introduction of the practice of queueing may enhance the experience. Waiting for more than one hour negatively impacts the visit experience and limiting Waiting Area 1 to a single section would enhance the visit experience. At the time of writing, due to COVID-19 visiting the Holy Rawda is completely different because of the need for social distancing and health measures, so this work offers insights to those planning the return to full operation after the pandemic has ceased.

References

1. Macal, C. and M. North. Introductory tutorial: Agent-based modeling and simulation. in Proceedings of the Winter Simulation Conference 2014. 2014. IEEE.

2. Alqasim, A., Colistin-resistant Gram-negative bacteria in Saudi Arabia: A literature review. Journal of King Saud University-Science, 2021. 33(8): p. 101610.

3. Vision2030.gov.sa. Saudi Vision 2030. The honor to serve the increasing number of Umrah Visitors in the best way possible 2019; Available from: https://vision2030.gov.sa/en/node/11.

4. Alshammari, S.M. and A.R. Mikler. Modeling Disease Spread at Global Mass Gatherings: Hajj as a Case Study. in 2015 International Conference on Healthcare Informatics. 2015. IEEE.

5. Al-Ahmadi, H.M., et al., Preparedness for Mass Gatherings: A Simulation-Based Framework for Flow Control and Management Using Crowd Monitoring Data. Arabian Journal for Science and Engineering, 2021. 46(5): p. 4985-4997.

6. Okazaki, S. and S. Matsushita. A study of simulation model for pedestrian movement with evacuation and queuing. in the International Conference on Engineering for Crowd Safety. 1993.

7. Gordon, G. A general-purpose systems simulation program. in Proceedings of the December 12-14, 1961, eastern joint computer conference: computers-key to total systems control. 1961.

8. Thalmann, D., Crowd simulation. Wiley Encyclopedia of Computer Science and Engineering, 2007.

9. Sung, M., M. Gleicher, and S. Chenney. Scalable behaviors for crowd simulation. in Computer Graphics Forum. 2004. Wiley Online Library.

10. Banks, J., J.S. CARSON II, and L. Barry, Discrete-event system simulation fourth edition. 2005, Pearson.

11. Altiok, T. and B. Melamed, Simulation modeling and analysis with Arena. 2010: Elsevier.

12. Von Sivers, I. and G. Köster, Dynamic stride length adaptation according to utility and personal space. Transportation Research Part B: Methodological, 2015. 74: p. 104-117.

13. Krahl, D. ExtendSim: a history of innovation. in Proceedings of the Winter Simulation Conference. 2012.

14. Box, G.E., All models are wrong, but some are useful. Robustness in Statistics, 1979. 202: p. 549.

15. The Agency of the General Presidency for the Affair of the Prophet's Mosque. [cited 2022; Available from: https://wmn.gov.sa.

16. Azeemi, M.F., HydraNetSim: a Parallel Discrete Event Simulator. 2012, School of Information and Communication Technology KTH Royal Institute of Technology,Stockholm, Sweden. p. 105.

17. Extendsim simulator. 2022; Available from: https://extendsim.com/.

18. The Custodian of the Two Holy Mosques Institute for Hajj and Umrah Research. 2022; Available from: https://uqu.edu.sa/en/hajj.

19. Greasley, A., Simulation modelling for business. 2017: Routledge.

20. M.Althabiti, N.A., A.Alkenani,N.Alfifi, M.Alzahrani, M.Abdullah Simulation Study of Shuttle Buses in Hajj, in Computing and Information Technology. 2015, King Abdul Aziz University. p. 84.

21. Rabe, M., S. Spieckermann, and S. Wenzel. A new procedure model for verification and validation in production and logistics simulation. in 2008 winter simulation conference. 2008. IEEE.

22. Straka, M., et al., Numeryczny model materiałowego przepływu procesu odzysku odpadów komunalnych. Przemysł Chemiczny, 2016. 95.

23. Groover, M.P., Automation, production systems, and computer-integrated manufacturing. 2016: Pearson Education India.

24. Degeling, K., et al., Matching the model with the evidence: comparing discrete event simulation and state-transition modeling for time-to-event predictions in a cost-effectiveness analysis of treatment in metastatic colorectal cancer patients. Cancer epidemiology, 2018. 57: p. 60-67.

25. Long, K.M. and G. Meadows, Simulation modelling in mental health: A systematic review. Journal of Simulation, 2018. 12(1): p. 76-85.

26. Howell, E.M., N.G. Kigozi, and J.C. Heunis, Community-based directly observed treatment for TB patients to improve HIV services: a cross-sectional study in a South African province. BMC health services research, 2018. 18(1): p. 255.

27. Iwańczyk, I., Arena simulation software as an example of the discrete event simulator. 2015.

28. Robinson, M. and S. Yorkstone, Becoming a lean university: The case of the University of St Andrews. Leadership and Governance in Higher Education: Handbook for Decision-Makers and Administrators, 2014.

29. Felemban, E.A., et al., Digital revolution for Hajj crowd management: a technology survey. IEEE Access, 2020. 8: p. 208583-208609.

30. Koshak, N. A GIS-based spatial-temporal visualization of pedestrian groups movement to and from Jamart area. in Proc. of International Conference on Computers in Urban Planning and Urban Management (CUPUM). 2005. Citeseer.

31. Narain, R., et al., Aggregate dynamics for dense crowd simulation, in ACM SIGGRAPH Asia 2009 papers. 2009. p. 1-8.

32. Zainuddin, Z., K. Thinakaran, and I.M. Abu-Sulyman, Simulating the Circumambulation of the Ka'aba using SimWalk. European Journal of Scientific Research, 2009. 38(3): p. 454-464.

33. Mulyana, W.W. and T.S. Gunawan. Hajj crowd simulation based on intelligent agent. in International Conference on Computer and Communication Engineering (ICCCE'10). 2010. IEEE.

34. Tunasar, C. Analytics driven master planning for mecca: Increasing the capacity while maintaining the spiritual context of hajj pilgrimage. in 2013 Winter Simulations Conference (WSC). 2013. IEEE.

35. Curtis, S., et al. Virtual tawaf: A case study in simulating the behavior of dense, heterogeneous crowds. in 2011 IEEE International Conference on Computer Vision Workshops (ICCV Workshops). 2011. IEEE.

36. Curtis, S., et al., Right of way. The Visual Computer, 2013. 29(12): p. 1277-1292.

37. Haghighati, R. and A. Hassan, Modeling the flow of crowd during tawaf at Masjid Al-Haram. Jurnal Mekanikal, 2013. 36(1).

38. Manenti, L., et al. An agent-based proxemic model for pedestrian and group dynamics: motivations and first experiments. in International Workshop on Multi-Agent Systems and Agent-Based Simulation. 2011. Springer.

39. Alonso-Marroquín, F., et al., A discrete spheropolygon model for calculation of stress in crowd dynamics, in Traffic and Granular Flow'13. 2015, Springer. p. 179-186.

40. Sakellariou, I., et al. Crowd formal modelling and simulation: The Sa'yee ritual. in 2014 14th UK Workshop on Computational Intelligence (UKCI). 2014. IEEE.

41. Rahman, A., et al. Towards accelerated agent-based crowd simulation for Hajj and Umrah. in 2015 International Symposium on Agents, Multi-Agent Systems and Robotics (ISAMSR). 2015. IEEE.

42. Dridi, M.H., Simulation of high density pedestrian flow: Microscopic model. arXiv preprint arXiv:1501.06496, 2015.

43. Kim, S., et al., Velocity-based modeling of physical interactions in dense crowds. The Visual Computer, 2015. 31(5): p. 541-555.

44. Nasir, F.M. and M.S. Sunar. Simulating large group behaviour in Tawaf crowd. in 2016 Asia Pacific Conference on Multimedia and Broadcasting (APMediaCast). 2016. IEEE.

45. Majid, A.R.M.A., et al., GPU-based Optimization of Pilgrim Simulation for Hajj and Umrah Rituals. Pertanika Journal of Science & Technology, 2018. 26(3).

46. Sarmady, S., F. Haron, and A.Z. Talib, Agent-Based Simulation Of Crowd At The Tawaf Area. 2007.

47. Sarmady, S., F. Haron, and A.Z. Talib, A cellular automata model for circular movements of pedestrians during Tawaf. Simulation Modelling Practice and Theory, 2011. 19(3): p. 969-985.

48. Curtis, S., et al., Virtual Tawaf: A velocity-space-based solution for simulating heterogeneous behavior in dense crowds, in Modeling, Simulation and Visual Analysis of Crowds. 2013, Springer. p. 181-209.

49. Shuaibu, A.N., et al. Collision avoidance path for pedestrian agent performing Tawaf. in Proceedings of the First International Conference on Advanced Data and Information Engineering (DaEng-2013). 2014. Springer.

50. Crociani, L., L. Manenti, and G. Vizzari. MAKKSim: MAS-based crowd simulations for designer's decision support. at the International Conference on Practical Applications of Agents and Multi-Agent Systems. 2013. Springer.

51. Al-Sabban, S.A. and H.M. Ramadan, A Simulation study of the shuttle-bus pilgrim transportation system between the Holy sites for the 1422H Hajj Season. Engineering Sciences, 2005. 16(2).

52. Reffat, R., An intelligent computational real-time virtual environment model for efficient crowd management. International Journal of Transportation Science and Technology, 2012. 1(4): p. 365-378.

53. Tayan, O. and A. Al-Binali, Evaluation of a proposed intelligent transportation framework using computer network concepts: A case study for Hajj-pilgrim traffic monitoring and control. International Journal of Computer Science Issues (IJCSI), 2013. 10(2 Part 2): p. 325.

54. Tayan, O., A.M. Al BinAli, and M.N. Kabir, Analytical and computer modelling of transportation systems for traffic bottleneck resolution: A Hajj case study. Arabian Journal for Science and Engineering, 2014. 39(10): p. 7013-7037.

55. Alshammari, S.M. and A.R. Mikler. Modeling Spread of Infectious Diseases at the Arrival Stage of Hajj. at the International Conference on Bioinformatics and Biomedical Engineering. 2018. Springer.

56. Khan, M.A., et al., Physicochemical properties and combustion kinetics of food waste derived hydrochars. Journal of King Saud University-Science, 2022: p. 101941.

57. Yasein, M.S., M. Al-Gamal, and M. Shambour, Crowd Movement Analysis in Al-Masjed Al-Nabawy using Modelling and Simulation. The Scientific Bulletin, 2013: p. 4.

58. Al-Ahmadi, H.M., et al., Statistical analysis of the crowd dynamics in Al-Masjid Al-Nabawi in the city of Medina, Saudi Arabia. International Journal of Crowd Science, 2018.

59. Alshehri, A., et al. Analysis of crowd movement in the prophet (saw) mosque in the city of madinah, saudi arabia. 2015. Proceedings of the Third Intlernational Conference on Advances in Computing ….

60. Oasys. Mass Motion. 2022; Available from: https://www.oasys-software.com/support/massmotion/.

61. Haron, F., et al., Software evaluation for crowd evacuation-case study: Al-masjid an-nabawi. International Journal of Computer Science Issues (IJCSI), 2012. 9(6): p. 128.

62. what is Exodus tool 2021; Available from: https://docs.exodus.tools/.

63. what is SIMWALK. 2022; Available from: https://www.simwalk.com/.

64. STEP tools,Inc. 2021; Available from: https://www.steptools.com/.

65. Korhonen, T. and S. Hostikka, Fire dynamics simulator with evacuation: FDS+ Evac: Technical reference and user's guide. 2009.

66. Siegfried, R., et al. A reference model for agent-based modeling and simulation. in Proceedings of the 2009 Spring Simulation Multiconference. 2009.

67. Barton, R.R. Simulation experiment design. in Proceedings of the 2010 Winter Simulation Conference. 2010. IEEE.

68. Shamai, S. and S. Verdú, The empirical distribution of good codes. IEEE Transactions on Information Theory, 1997. 43(3): p. 836-846.

69. Balci, O. Verification, validation, and accreditation. In 1998 winter simulation conference. proceedings (cat. no. 98ch36274). 1998. IEEE.

70. Moffat, J., Adapting modeling & simulation for network enabled operations. 2011, OFFICE OF THE ASSISTANT SECRETARY OF DEFENSE FOR NETWORKS AND INFORMATION.