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Modelling Mass Crowd Using Discrete Event Simulation: A Case Study of Integrated Tawaf and Sayee Rituals During Hajj

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ABSTRACT Hajj is a mass gathering event that takes place annually in Makkah, Saudi Arabia. Typically, around three million people participate in the event and perform rituals that involve their movements within strict space and time restrictions. Despite efforts by the Hajj organisers, such massive crowd gathering and movement cause overcrowding related problems at the Hajj sites. Several previous simulation studies on Hajj focused on the rituals individually. Tawaf, followed by Sayee, are two important rituals that are performed by all the pilgrims at the same venue on the same day. These events have a strong potential for crowd buildup and related problems. As opposed the previous works in the literature, in this paper we study these two events jointly, rather than separately. We use ExtendSim, a Discrete Event Simulation tool, to integrate the Tawaf and Sayee rituals into one model. The validated model was applied to a wide range of scenarios where different percentages of pilgrims were allocated to the various Tawaf and Sayee areas. The effect of such allocations on the time to complete Tawaf and Sayee indicate strategies for managing these two key Hajj rituals.

INDEX TERMS Hajj, Tawaf, Sayee, crowd management, crowd modelling, crowd simulation, evacuation modelling, evacuation simulation, ExtendSim.

I. INTRODUCTION

Mass Gathering (MG) events involve participation of more than 1,000 people in one site at the same time [1] for a specific purpose and for a finite duration [2]. MG events can be religious (e.g., Hajj); cultural (e.g., large music concerts); sporting (e.g., the Olympics and FIFA World Cups); or political (e.g., processions and rallies or social riots) [3]. Because of the large number of attendees, MGs pose many challenges such as crowd management, security and emergency readiness [2]. If these challenges are not well managed, MGs can result in adverse outcomes, including spread of diseases, crashes, stampedes, traffic incidents, fires, leading to injuries and even fatalities [2].

Hajj, the pilgrimage to Makkah in Saudi Arabia, takes place at several holy sites every year between 8th and 12th of Dhulhijjah, the 12th month in the Islamic (lunar) calendar [4]. With a crowd of up to three million people comprised of Muslims from all over the world, Hajj is the largest annual MG globally [5]–[9]. With an already large and ordinarily increasing numbers of pilgrims each year, Hajj authorities will continue to face bigger challenges, primarily relating to the safety and security of pilgrims [11]. Given the uniqueness of the event, the complexity of the planning associated with Hajj, its impacts [12], and the anticipation that Hajj attendance will increase post-COVID19 pandemic, a rigorous and

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integrated study of Hajj from a crowd management perspective is timely and essential.

Hajj rituals are performed at several sites during the five days within specific time windows. It requires all pilgrims to move from one site to another by bus, train, or on foot [4], [10].

Past studies of Hajj have focused on individual rituals. However, the rituals are closely linked, and involve mass movement of pilgrims from one site to another in a fixed and short time period. Thus, congestions are not only at individual sites, but also between sites and rituals.

This paper focuses on the two rituals performed in the Grand Mosque (GM) during Hajj, on the 3rd day of Hajj: Tawaf Al-ifadah (walking in a counter-clockwise direction seven times around the Ka'aba); and Sayee (pilgrims walk and/or run seven times back and forth) between the two hills of Al-Safa and Al-Marwah, close to the Tawaf area [9].

The objective of our work is to simulate and validate the real Hajj data in various crowd conditions, assessing to what extent capacity and behavioural aspects contribute to crowding and congestion within the Grand Mosque area. Whereas many scholars focused on a single ritual, this research combines two of the most demanding rituals during Hajj, completed within the confines of the GM and with the potential to affect each other.

We use a Discrete Event Simulation (DES) software as a tool to model and simulate the integrated Tawaf and Sayee rituals at normal and evacuation situations. After validating the models, we developed scenarios to study and evaluate the effect of changes in pilgrim distributions at the GM. Given the features of Hajj events (large mass size, geographical setting, time restrictions and annual recurrence of the event), a comparison with other MG events may not be appropriate. Yet, practical solutions we offer here could be applicable to other mass gathering events (e.g., music festivals, Olympics).

The rest of this paper is structured as follows. Section II presents a literature review on Hajj, crowd models and simulation. Section III details the data resources and methodology. Section IV describes the design and implementation of Tawaf and Sayee in ExtendSim. Section V describes how the simulation models for Tawaf and Sayee rituals were validated and the development of various scenarios for these rituals. In Section VI is we discuss the study results and the implications of the scenarios. The paper concludes with Section VII providing general insights from the modelling exercise, discussing limitations and recommendations for future work.

II. LITERATURE REVIEW

A. HAJJ CHARACTERISTICS

Hajj consists of complex and intense activities (rituals) in a prescribed sequence [4], [11]. The planning of pilgrim movements and transport from one site to another during the event is an enormous task [11], [9]. Strictly marked territorial boundaries of the specific Hajj sites limit the capacities of the sites. For instance, the areas for Tawaf (called Mataf) and Sayee each accommodate only tens of thousands of persons at any one time. This is only one of the indicators of these challenges, given that around three million pilgrims need to perform these two rituals on the same day in sequence [13]. Osman and Shaout [6] mention additional reasons that make Hajj crowd management a 'tough task': pilgrims come from all over the world and have different backgrounds, languages and cultures, which is often reflected in their behaviours during Hajj.

Pilgrim groups are managed by Hosting Agencies called Mutawif or National Establishments. There are eight establishments: Locals; Arabic Gulf; Iran; South East Asia (SEA); Southern Asia (SA); Africa; Arabs; with the final establishment comprising Turkey, Europe, Australia and America (TEAA) [14]. Each establishment has clearly assigned accommodation at the Hajj sites and scheduled times for rituals [15]. Pilgrims are organised into groups (of usually 250 pilgrims) with a guide [16]. The guides are in charge of their groups throughout the whole Hajj, instructing them on the rules, providing the schedule of activities, leading the groups through movements (following dedicated routes and means of transport), and monitoring the progression of rituals [17]. When performing the sequence of activities, the whole group must slow or stop the progression of an activity to accommodate the needs of the group members. Many pilgrims do perform the Hajj rituals independently of their group, on their own and/or with their family and friends. Nonetheless transport and accommodation of pilgrims are organised by their Hajj groups.

B. CROWD MANAGEMENT

Crowd management or systematic planning aimed at optimally managing the movements and assembly of people [11] is an evolving field of interest for specialists in computing, health and police enforcement. Alabdulkarim *et al.* [18] described crowd management as: "…a practice that is used to control crowd events before, during, and after events, which include dealing with all elements of an event such as people, sites, facilities, data and technology" (p.251).

Hajj provides a unique case study of crowd management, as it involves the management of a very large number of pilgrims gathered at the same time and place [15]. Inadequate crowd management can lead to high levels of crowd density and overcrowding, which in turn may have deleterious effects on participants' safety [17]. As indicated, the outcomes range from minor (getting lost), to moderate (injuries, heat exposure) and major (crushing disasters, deaths) [4], [6], [9], [10], [18], [19]. These incidents are attributed to human bottlenecks, heavy crowds, and unsuccessful crowd movement control [20], [21], [11], [18]. More details about previous Hajj incidents can be found in Owaidah *et al.* [19]. In addition to overcrowding at Hajj sites, problems with pilgrim movements and transport [22] could lead to uncontainable buildup of crowds for the activities that follow [4].

C. CROWD MODELLING

Hajj requires substantial prior planning using various possible scenarios [8], [23]. Such planning, achieved by using crowd modelling and simulation, plays a vital role in anticipating and preventing crowd evacuation problems before they occur [3], [24]. Modelling (including simulation) offers many benefits: developing prior arrangements; improving crowd and transport management; identifying crowded spots and traffic bottlenecks; and investigating transitions from normal to evacuation scenarios. In addition, using crowd modelling helps to investigate why, where, when, and how crowds move and leave an event or venue. Crowd modelling assists modellers and practitioners to develop safe and robust prior planning for crowd management [13].

Modelling efforts in the literature have focused on four types of dangers associated with crowds in extreme conditions: trampling and crushing at religious sites (e.g., Hajj event); trampling and crushing on ships at sea or waterways; crushing during massive concerts; and crowd trampling during natural disasters (earthquakes, floods, avalanches or landslides) [24]. However, crowd modelling and simulation prior to an event can replicate scenarios of safety in risk-free, low cost, time-independent and casualty-free experimental environments. For example, modellers can gain insights into the causes of overcrowding and compare performances of various design alternatives [3].

The following section reviews previous studies on modelling and simulating the rituals of Tawaf and Sayee.

D. CROWD MODELLING AND SIMULATION FOR HAJJ EVENTS

Owaidah *et al.* [19] presented a systematic review of crowd modelling and simulation models, especially those applied for Hajj. They concluded that simulation (DES, Agent Based Models, ABM) combined with Support Vector Machines (SVMs) or other models is the prevailing approach. Crowd modelling and simulation for Hajj event is one of the significant technologies that is used the planning processes of Hajj crowd management [9]. Here we briefly present some of the key literature relevant to Tawaf and Sayee.

Haghighati and Hassan [13] investigated the effect of various crowd problems during Tawaf, with the aim of improving the pilgrim movements around the Ka'bah and reducing the congestion inside the Grand Mosque. Their simulation was conducted using a DES model developed in ARENA, considering the pilgrims as discrete units entering the system, moving through components, and then exiting the system. Pilgrims had specific attributes (e.g., gender, speed, and size) and were generated and 'stored' in queues. They then moved around the Ka'bah seven times in an anticlockwise route, and upon reaching the finishing line, left the Tawaf area for Sayee. The movement rule enabled each entity to walk in paths near to the Ka'bah whenever free space was available. The authors suggested using scheduling, spiral paths, and clear separation of pilgrim groups during Tawaf to reduce the average time for completing this ritual.

Abdelghany *et al.* [25] developed a hybrid simulation-assignment modelling framework, which integrates two layers. The first layer is a network layer, representing the study facility, enabling the pilgrims/entities to plan their routes, while performing their activities. The second layer is a cellular automata (CA) model, which describes each movement according to a sequence of cells occupied over time by an entity until reaching the destination. Their study focused on studying crowd dynamics in large-scale pedestrian facilities, to identify congestion at the Mataf. The cell dimension was selected based on the LoS F (7–8 people/m^2), which is usually recorded at Hajj during peak hours. They derived pilgrim density and flow rates at different distances from the Ka'aba (e.g., 8 pilgrims/m^2 around the Ka'aba and decreasing to 4 pilgrims/m^2 to the surrounding edges/walls of the Tawaf. The model was validated and the results showed a low flow rate of about 50 pilgrims/m/s around Ka'aba, but increased further away from it, resulting in a capacity of 40,000 pilgrims/h for the Tawaf. Although this work offers a description of the Tawaf and Sayee areas, it only presents results from the Tawaf area, and does not consider other Tawaf levels or the Sayee.

To understand crowd behaviour, Nasir and Sunar [26] focused on studying the simulation of pilgrim groups in normal conditions, using a popular technique to simulate large groups, the Social Force Model (SFM), combined with a flocking technique. Their study also focuses on the Tawaf area, and their model was built on Microsoft Visual Studio 2013 and written using the C++ programming language. The model's graphics were made using the Open Graphics Library (OpenGL) and application programming interface (API). The results of simulating 500 agents showed that group members successfully maintained their position and kept close to each other in the crowd. If one of them was behind, the whole group would reduce its speed and wait for the individual to catch-up with the rest of the group. This micro-level study highlighted important details of crowd movement in normal situation in the Tawaf area, but the number of entities modelled does not reflect the actual capacity (40,000 to 50,000 pilgrims/h). This study did not consider where and why the simulated pilgrims may change their speed during Tawaf and how pilgrims can be managed at high-density spots.

Felemban *et al.* [27] built a crowd simulation model in MassMotion software to study the crowd's movement patterns around the Ka'aba, including entering and exiting from the Tawaf area, stopping to kiss the Black Stone, and slowing down at the starting line of each circumambulation. Felemban *et al.* [27] analysed the crowd density around the Kaaba and calculated the required total time for completing the Tawaf ritual in high density and less crowded situations. The micro-level simulation enabled recording individual data on the time and location of entering the Tawaf area, the walking distance and average speed of the Tawaf performance and the number of circumambulations completed when the simulation is stopped. However, this study did not report any results of the simulations.

Löhner *et al.* [28] presented two SFM models to understand pilgrim motions when the Tawaf area is congested. The first model focused on modelling and simulating the pilgrims at their desired distance to the Ka'aba, while the second model simulated pilgrims getting closer to the Ka'aba where they reach the highest crowd density. The authors used the ''PEDFLOW'' crowd dynamics simulation tool to build these two models. The parameters included were the geometry of the Grand Mosque, the entry/exit points to and from the Tawaf area, as well as pilgrim characteristics, such as their cultural background and fitness state. The model simulated 32,400 p/h. The simulation results from the first model showed that the pilgrim density was low in the left region of the Ka'aba, where pilgrims are far from the starting line, yet the density of pilgrims increases close to the Ka'aba, as shown by the second model. The authors suggested a self-regulation process whereby ''If the density increases too much, the pilgrims move further away from the Ka'aba and the simulation proceeds without problems while still being realistic'' (p.530). The study has not mentioned the fitness level of the pilgrims, their age or gender.

Mohamed and Parvez [29] proposed a Finite State Machine (FSM) based model for modelling and simulating pilgrim movements during Tawaf. In particular, the authors showed that crowding around the Black Stone 'to touch and kiss' could result in aggressive behaviours of the pilgrims, with the elderly and women being excluded from this ritual. Their simulation investigated innovative ways to manage the crowd around the Black Stone by specifying times for various groups, forming dedicated queues, and introducing physical barriers. The authors compared: the average time of pilgrims to complete the Tawaf (with or without kissing the Black Stone and including queuing) and the average time for pilgrims to 'touch and kiss' the Black Stone (including queuing); the average time to perform Tawaf and queuing behind a barrier installed besides the wall of Ka'aba (the proposed system). They also highlighted the benefits of the physical barrier, which would compel the pilgrims to queue without having to struggle or overcrowd around the Black Stone. However, although the authors specified crowd density as Level of Service (LoS, representing the number of pilgrims/m^2), they did not mention the overall number of pilgrims simulated for performing the Tawaf ritual. Their findings led to new measures being adopted at Hajj, using security guards and organising pilgrims to line-up; yet these measures have not been completely successful in preventing overcrowding or managing aggressive crowd behaviour.

Adopting the same SFM technique, Kolivand *et al.* [30] simulated pilgrim movements at the Tawaf area more ''realistically'' by designing a high-density crowd simulation model that accounts for pilgrim characteristics such as gender, walking speed, and grouping and stopping in the crowd. Their simulation results showed that increasing the number of pilgrims/entities leads to frequent stops in the crowd (either slowly or suddenly), because of the interactions with the surrounding pilgrims (overcrowding). The model closely mimicked the average walking speed during the Tawaf 0.35 m/s compared to 0.3267 m/s from collected data, for a number of 45,000 pilgrims. However, the authors have not highlighted the potential bottleneck areas in the Tawaf (where pilgrims stopped).

In conclusion, prior scholarly work considered congestion in the Tawaf area (one of the most challenging aspects of Hajj), focusing on aspects which can change the physical design of the area. The simulations were at micro-level and adopted techniques, such as CA or SFM, well-suited for inter-agent interactions, although most of them presented results on a relatively small scale compared to the real event. Yet, if the aim is to identify planning and management/operation aspects that can be implemented in Hajj (e.g., scheduling the sequence of activities by groups), adopting a macro-level approach (and using for example discrete event simulations) is needed.

E. EVACUATION MODELLING AND SIMULATION FOR HAJJ EVENTS

Crowd evacuation simulation is a part of evacuation management, an important field of study to develop evacuation plans [31]. These plans can be executed to avoid crowd incidents at large places such as the GM and for huge events (e.g., Hajj events) [31]. As pilgrim numbers increase every year, studying and modelling pilgrim movements is important to improve Hajj crowd management and deliver safety during the event [32]. Although many pilgrims are informed and some are trained to perform the Hajj rituals, very few - if any - are trained to react to emergency or evacuation situations [33].

Therefore, due to the complex structures of Hajj sites and buildings, evacuation management deserves more attention by considering different evacuation scenarios at different Hajj locations [32], [33]. In addition, although studies have separately examined evacuation from Tawaf [32] or Sayee [34], there is no modelling developing combined Tawaf and Sayee evacuation scenarios. Our approach is to simulate the evacuation of groups of pilgrims from the GM at a more macroscopic level, by considering the group, instead of individual, as a moving unit [35].

Halabi [36] used the Space Syntax Laboratory to identify overcrowding hotspots and to show the spatial movements of the pilgrims during their evacuation from the Tawaf area of the Grand Mosque. They used spatial layouts and visual graph analysis to visualise the spaces inside the GM building. To develop the evacuation processes, Halabi [36] included several factors to calculate the duration of the evacuation, including the capacity of an area, walking speed and the distances to the exits. Their main findings of the evacuation processes are presented in **Table 1**. LoS E, equivalent to 6p/m^2, was applied in the evacuation processes, the average

TABLE 1. Halabi [36] evacuation results.

Level of GM	Level capacity (No. Pilgrim)	Number of exits during the evacuation	**Total time for evacuation (min)**	No. of pilgrims evacuated	No. of groups evacuated
Basement (Tawaf area)	52,800	20	**2.15**	44,210	176.84
Ground level	142,208	60	**13.73**	277,938 (135,730 from other levels)	1,111.75
1st level	91,250	21	**7.98**	91,250	356
Roof level	96,800	1 30 escalators*	**22.36**	96,800	387.2

* In this study, we replaced escalators with further distances to the gates.

speed being 46 m per minute (0.767 m/s), and pilgrim flow being 82 pilgrims/minute/m.

Halabi [36] concluded that pilgrims need substantially more time to be evacuated from the GM than was expected. Note that these evacuation processes were tested before the construction of King Abdullah expansion.

Abdelghany *et al.* [34] developed a CA framework of the Sayee area at the GM, where the evacuees could make their own decisions (such as exit choice, path choice to the exit, and path updating) to prevent collisions. Two main factors were considered when choosing an exit; the distance to evacuation exits (12 gates) and the congestion around the exits. The evacuation was developed in five experimental sets. The first set investigated the evacuation of 5,000, 15,000 and 25,000 pilgrims, corresponding to LoS of 0.4, 1.2 and 2.0 p/m^2 respectively. The second set investigated the evacuation under three density values, 100%, 60% and 20% and the 5th set focused on how the congestion awareness (40%, 60%, 80% and 100%, as proportions of the occupied cells) could affect the evacuation process. The main results of Abdelghany *et al.* [34] are presented in **Table 2**. Our interest is on the 1st, 2nd and 5th sets (more related to our case study).

TABLE 2. Abdelghany *et al.* [34] evacuation results.

Set of experiments	The main feature of the set			**Total evacuation duration (min)**
First set	LoS (p/m^2)	0.4	5,000	**9.97**
		1.2	15,000	**32.10**
		2.0	25,000	**47.08**
Second set	Density at the gate (%)	100	15,000	**20.62**
		60		**19.32**
		20		**18.88**
Fifth set	Congestion perception (awareness) (%)	100	15,000	**16.6**
		80		**18.6**
		60		**16.1**
		40		**21.0**

Abdelghany *et al.* [34] concluded that the evacuation performance (duration) could be improved if pilgrims had knowledge of and were trained on how to choose gates and follow evacuation procedures (such as choose the closest gates or less congested gates).

Recently, Mahmood *et al.* [3] developed an ABM in Any logic to identify, evaluate, and test emergency strategies in crowd evacuation. These strategies were tested in evacuating 10,000 pilgrims from the Tawaf area using 12 gates [3], as follows.

- Random gate evacuation: selecting any exit, simulating the crowd behaviour in panic.
- Shortest distance: choosing the nearest exits and considering prevention of collision.
- Genetic Algorithm (GA[1]): generating 'fit pilgrims' as a key function in the evacuation processes.

Mahmood *et al.* [3] considered the following common factors in the evacuation simulation: population = 10,000 pilgrims; min speed = 1.0 m/s, max speed = 2.0 m/s and most likely speed 1.4 m/s; number of simulation runs = 10. Optimisation reduced the evacuation time from 7.4 min (random gate) to 4 min (when the nearest gate was selected), and to 3.1 min when applying GA.

Mahmood *et al.* [3] underlined that the evacuation performance may differ from the presented results if evacuation scenarios simulate large numbers of pilgrims with more physical and behavioural interactions and collision prevention.

F. CONTRIBUTION OF THE WORK

This work aims to simulate and validate the real data of Hajj event 2019 in various crowd conditions (normal and emergency), to evaluate the potential changes of pilgrims' organisation inside the Grand Mosque. Scenarios of different crowd conditions are presented, and to identify the bottleneck spots during the Tawaf and Sayee rituals.

Furthermore, while a number of previous studies focused on modelling and simulating pilgrims on a single ritual at a time and at the individual level, this research combines both Tawaf and Sayee rituals, focusing on the relations between them. We used a DES software, ExtendSim, to focus on the potential implications for planning and managing the pilgrim activities at the Grand Mosque. This work is based on the validation of joint events (Tawaf and Sayee) and we applied well-established techniques to model crowds at the meso/macro level, to emphasise that infrastructure and behavioural aspects equally contribute to safety and efficient procedures and decision-making during Hajj. The results of sensitivity analysis are presented to identify elements that Hajj authorities may apply to more efficiently manage the crowds at the GM. Based on this analysis, we present some managerial solutions for crowd management at Hajj.

[1]GA is an optimisation technique using evolutionary concepts to choose the best evacuation solution that reduces the overall evacuation time by assigning pilgrims to less crowded exits.

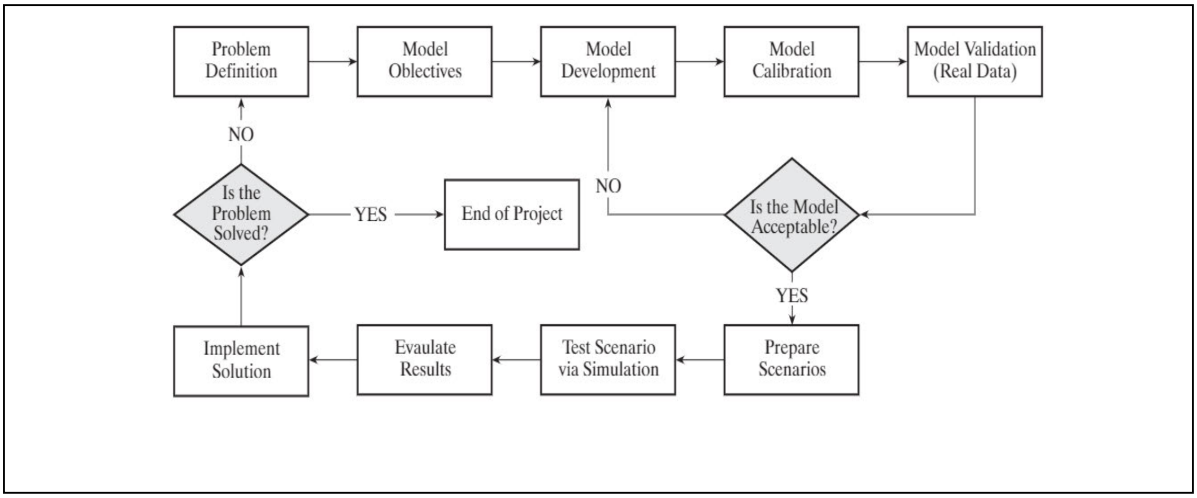


FIGURE 1. Diagram showing the modelling and simulation steps (with permission from Papageorgiou *et al.*, 2009, p.44) [39].

III. DATA RESOURCES AND METHODOLOGY

This study uses DES, focusing on Tawaf and Sayee rituals during the 10th of Dullhijjah, simulating both rituals as an integrated activity, in normal and evacuation situations, thus addressing a critical gap in the literature.

We used secondary data collected by the local Hajj authorities in Saudi Arabia and apply a model built in ExtendSim, a powerful platform for DES [37] developed by Imagine That Inc. [38]. The modelling approach was adapted from Papageorgiou *et al.* [39]. **FIGURE 1** illustrates the main steps, which are detailed below.

- Problem definition – clearly identifying the problem to be solved and its causes (e.g., why is there overcrowding at Hajj ritual locations, such as at Tawaf and Sayee areas).
- Model objectives – establishing the goals of the simulation, ensuring that the stated objectives solve the problem identified in the first step. In addition, the main system components are defined and the model inputs are identified. Our objective was to identify the locations that are subject to overcrowding and reduce the pilgrim numbers at these locations.
- Model development – model complexity required to achieve the stated objectives, as well as selecting the appropriate modelling platform. In our case, we have chosen ExtendSim10 for its capabilities and availability within the institution for research and training.
- Model calibration – refers to specifying the main mathematical equations and statistical functions used for building the model and using data to estimate the model parameters. We based our calibration on statistical information from secondary sources (official statistics of pilgrim numbers performing Tawaf and Sayee rituals and counts and durations estimated from video material) as well as previous scholarly work. In addition, given the uncertainties around several inputs, the model was tested with various input ranges e.g., distribution of times, number of services (number of gates, buses, etc.), walking speed of pilgrims, to test the robustness of the model.
- Model validation – using real data to test the model performance. This may involve developing criteria and applying statistical methods to test hypotheses. If the results between the simulation results and real-world data are different, the developer must check and update the model, then repeat this step again. The t-tests and MANOVA we applied indicate validation with 2015-2019 data.
- Scenario testing – developing and testing various scenarios once model validation is confirmed, evaluating the results, and formulating solutions.

A. DATA COLLECTION SOURCES

Secondary data were obtained from The Institute of Hajj and Umrah Research and Ministry of Hajj, Makkah city, Saudi Arabia. As shown in **FIGURE 2**, we combined many different sources to initialise and validate the models, including images and video recording from Hajj 2015, 2016 and 2017, tables and figures from Hajj 2019 operational planning, Hajj Transport Department and The Saudi Car Syndicate Operational Planning. Also included were social media coverage of Hajj daily reports in 2019, and personal experiences and recollections of previous Hajj events by co-authors. These data sources were compared, triangulated, and cross-checked before the model inputs were set, and the results of the simulation were compared with the published statistics of the events and media reports.

B. MODEL DEVELOPMENT

ExtendSim can simulate a variety of systems from simple to very complex stochastic models, which makes it applicable to many different fields such as healthcare, manufacturing,

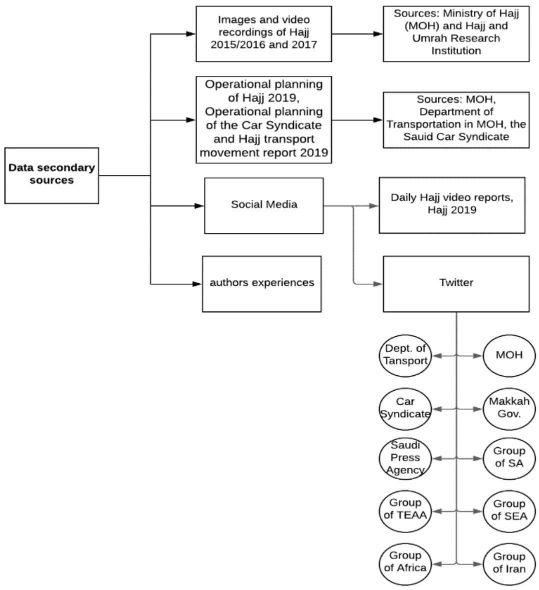


FIGURE 2. Data sources and data formation process.

communications, logistics and military operations [38], [40]. The platform implements a graphical interface consisting of many hierarchical blocks and including components that represent the processes in the simulation [40]. Blocks are the main items in ExtendSim, which progresses the items (entities or pilgrims) from one block to another to perform a specific activity [41].

IV. MODELLING AND SIMULATION IMPLEMENTATION

The model presented here refers to the Tawaf and Sayee rituals performed in the GM assuming the pilgrims are already in Makkah. Activities undertaken prior by international and regional pilgrims are not modelled in this simulation. Note that some figures and maps are stored in the institutional repository for better resolution.

A. TAWAF AND SAYEE AT THE GRAND MOSQUE

The Grand Mosque is a large complex area which covers 356,800 m^2 [42]–[44], with expansion plans to 1.1 million m^2 to accommodate up to 2.5 million worshippers at a time [44]. The last expansion, initiated in 2011, was paused in 2015 after a crane accident (which caused 111 fatalities and 394 injuries), but resumed in 2017 [45]. The expansion has reached 80% completion and is expected to be finished in 2022 [46]. The Tawaf area consists of the following sections [47]–[49].

- Tawaf area around the Ka'aba (or simply Tawaf) has an extended area of 16,185 m^2 and permits 50,000 pilgrims per hour (p/h) [5], [48].
- Ground level with area 11,778 m^2 and permits between 10,000 to 25,000 pilgrims p/h.
- Level 1 has an area 10,318 m^2 and allows between 7,000 to 26,000 pilgrims p/h.
- Roof Level has an area 10,318 m^2 and allows for 12,000 to 30,000 pilgrims p/h. Capacity on Level 1 and roof levels are different, because of the different pilgrim speeds on these levels.

The Tawaf (154 m long and 105 m wide) includes a circular area [48], with the Ka'aba in the middle. The walking distances vary between 200 m and 585 m per circle [50], leading to circumambulation distances between 1.4 to 4.1 km (depending on where it is performed). The overall average level of services (LoS) is 4 pilgrims/m^2, which is considered high density [17]. However, at certain locations such as the Tawaf, the preferred area by pilgrims [13], the LoS can reach to 6-8 pilgrims /m^2 [17].

To avoid congestion, pilgrims are distributed over the five levels as follows: Tawaf area (73.2%); Ground level (GL) (12.7%); Level 1 (L1) (11.1%); Mobility Reduced area at Level 1 (L1 MR) (2%) and Roof (RL) (1%).

Currently, pilgrims use five major gates to access the GM; Al-Umrah (U), King Fahad (K.F.), King Abdulaziz (K.Az), Al-Marwah (M), and Al-Fatah (F) [51]. King Abdulaziz gate (K.A.) (bottom of map, **FIGURE 3**) is the nearest to the beginning line of the Tawaf ritual [51] and the most used gate. With the new expansion of the GM, a sixth gate, called King Abdullah Gate (K.A.) (north west of the map), leads directly to the Tawaf area [46]. GM has a total of 179 gates (indicated in blue in **FIGURE 3**).

Tawaf Al-ifadah is obligatory for Hajj completion [52], being a key ritual. Pilgrims arrive at Mina on the 8th of Dhulhijjah and leave for Arafat on the 9th, spending the whole day there. Just before sunset, they leave for Muzdalifah where they spend the night. Usually pilgrims perform Tawaf after noon on the 10th, after stoning the big Aljamarat pillar, sacrificing an animal and shaving their heads [42], [43], [53]. Tawaf Al-ifadah needs to be completed within a 48-hour window on the 10th and 11th [53].

After performing Tawaf, pilgrims must go to the Sayee area, about 400m away, but still within the boundaries of the GM [55]. The Sayee ritual requires pilgrims to move back and forth between the two hills of Al-Safa and Al-Marwah seven times, starting from Al-Safa (**FIGURE 3**) [50], [56]. The Sayee area is about 394 m long and 33 m wide [56]. Sayee can be performed at any one of five levels, each with an estimated capacity of 50,000 pilgrims and a maximum crowd density during the peak of Hajj of about 4 pilgrims/m^2 [34]. The highest allocation is for the Ground-level (57.5%), which is a continuation of the Tawaf area. Pilgrims are distributed to other Sayee levels as follows: Basement level (BL) (15.5%); Level 1 (L1) (22%); Mobility Reduced area at Sayee first level (L1 MR) (1%); Level 2 (L2) (3%) and Level 3 (L3) (1%). There is no strict requirement as to which establishments to perform Sayee at each level, but pilgrims' preferences match the percentages above.

FIGURE 4 shows the percentage of pilgrims and the corresponding LoS for each level of the Tawaf and Sayee areas. For example, when the percentage of pilgrims in the

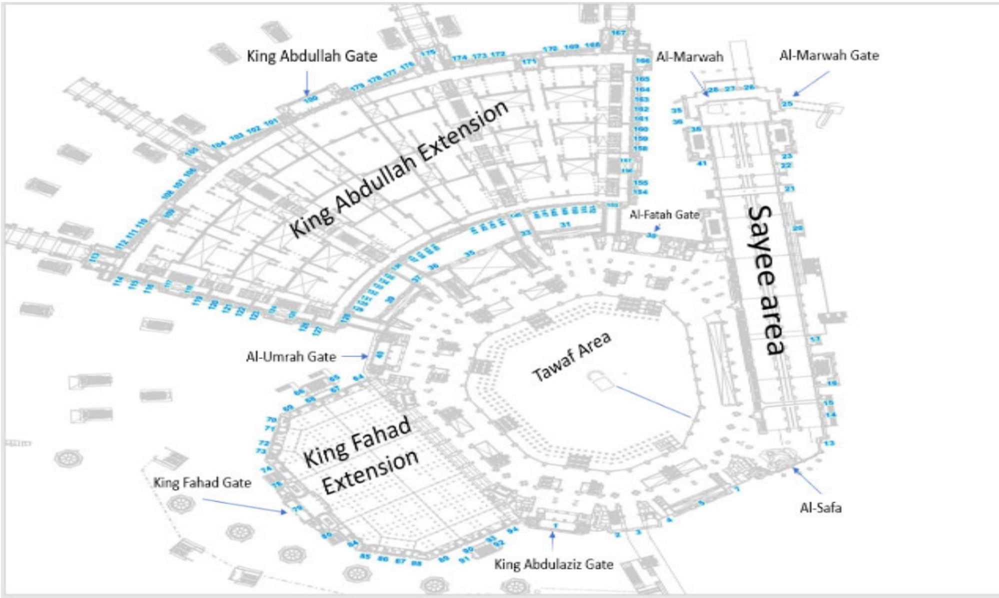
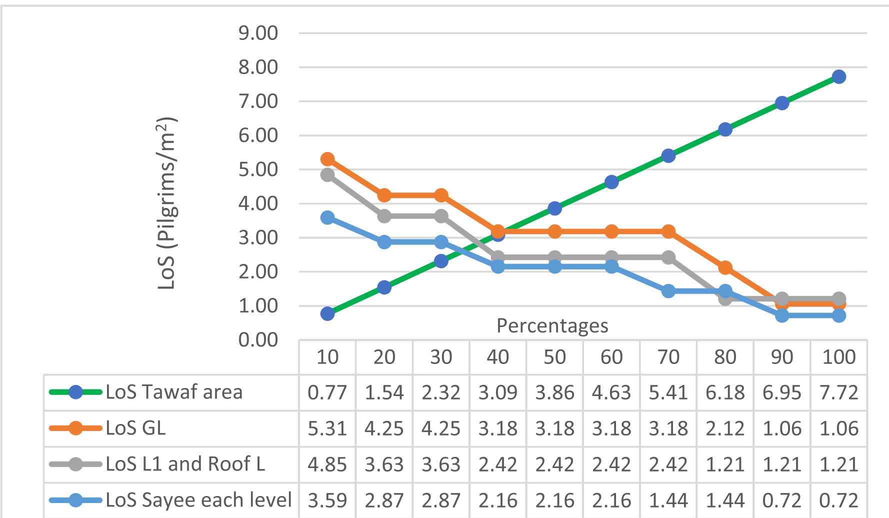


FIGURE 3. **The Grand Mosque map (source: The General Presidency of The Affairs of The Grand Mosque and The Prophet's Mosque, 2020) [54].**



	10	20	30	40	50	60	70	80	90	100
LoS Tawaf area	0.77	1.54	2.32	3.09	3.86	4.63	5.41	6.18	6.95	7.72
LoS GL	5.31	4.25	4.25	3.18	3.18	3.18	3.18	2.12	1.06	1.06
LoS L1 and Roof L	4.85	3.63	3.63	2.42	2.42	2.42	2.42	1.21	1.21	1.21
LoS Sayee each level	3.59	2.87	2.87	2.16	2.16	2.16	1.44	1.44	0.72	0.72

FIGURE 4. **LoS depending on the allocation percentages.**

Tawaf area is 30%, the LoS is 2 pilgrims/m^2, but this increases to 6 pilgrims/m^2 when the allocation becomes 80%. Correspondingly, the allocation in other areas decreases, resulting in an improved LoS. The most dramatic effect is seen for GL, and L1 and the roof level, given their reduced allocation.

Other studies have shown that by maintaining the number of pilgrims in the Tawaf area at a maximum of 50% for all activities [17], [48] a better utilisation of infrastructure is achieved and a LoS under 6 pilgrims/m^2 is ensured (see **FIGURE 4**).

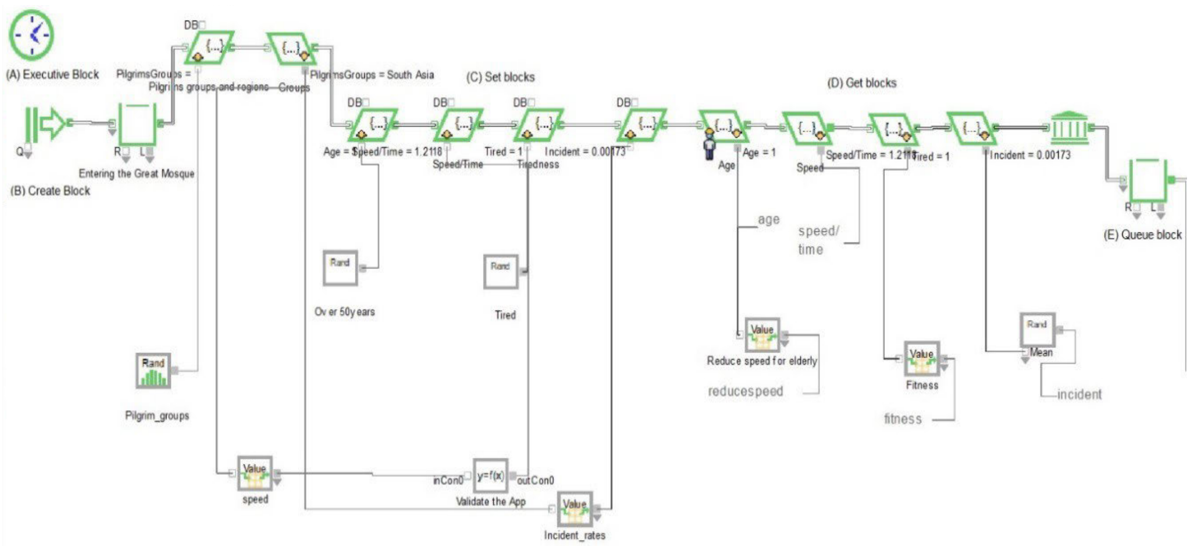


FIGURE 5. (A) Executive Block, (B) Create Block, (C) Set Blocks, (D) Get Blocks, (E) Queue Block.

B. TAWAF AND SAYEE SIMULATION

The simulation model in ExtendSim includes sets of hierarchical blocks, each performing a specific activity [57]. **Table 13** (in the appendix) presents the main blocks used in our model along with their functions. An Executive Block (**FIGURE 5-A**), located at the top left corner of the model, controls the simulation timing and passage of the pilgrims through the system. Create blocks generate pilgrims, Set blocks assign behavioural characteristics to pilgrims and Activity blocks are used for the duration of the rituals.

In the Tawaf and Sayee model (**FIGURE 5**), the Create Block (**FIGURE 5-B**[3]) generates 12,000 groups of 250 pilgrims each, giving a total of three million pilgrims. Pilgrims enter the Grand Mosque, perform Tawaf followed by Sayee, and then exit the simulation. The following attributes were applied to pilgrims and were incorporated using Set and Get Blocks (**FIGURE 5-B, C and D**[3]).

- **Groups and regions:** as percentages of all pilgrims for Hajj 2019.
- **Age:** The available data of pilgrims ages from Hajj 2019, used for validation, was by category (under and over 50). 40% aged between 10 and 50 years and 60% aged 50 years+, each with different fixed fitness levels.
- **Speed:** Speeds vary between 0.8 to 1.46 (m/s) depending on pilgrims' fitness and level of fatigue (three levels assumed - rested, tired and very tired) and are given in **Table 14** (Appendix). The average walking speed for the ages 10-50 (fit) is around 1 m/s and for elderly pilgrims is 0.83 m/s. Triangular distributions are applied with the average speeds being the most likely speeds. Additional speed adjustment is applied for crowding, when the speed is halved for LoS above 4 people/m^2.
- **Fatigue:** This attribute is related to the Speed attribute. After walking for a period of time, pilgrims' level of energy is assumed to change from rested to tired and their speed drops by a factor of 1.11. This further changes from tired to very tired and their speed decreases by a factor of 1.25 compared to rested. These average levels were established based on the video material, but were also tested as a part of the sensitivity analysis.
- **Incident rates:** Bianchi [58] reported that eight countries from four different continents faced major incidents at Hajj events between 2002-2015. Percentages of incidents were calculated by geographical groups (Iran, Indonesia, Pakistan, Bangladesh and India together under Asia; Turkey was combined with Europe; Nigeria under Africa, and Egypt under Arab countries). The incident rates for these groups (**Table 15** in the Appendix) vary from Iran = 0.06%, Europe = 0.07% to South Asia = 0.53%).

Pilgrim arrivals are scheduled by the Hajj authorities. For example, Hajj authorities allow a time window of six hours for each group to arrive at the Grand Mosque from Mina city on the 10th, perform Tawaf and Sayee then exit and return to Mina. The arrival rates largely follow a Poisson distribution.

The distribution of the pilgrims in the model was based on the following statistics:

- Africa 7.11% (12 pm – 6 pm on the 10th)
- Arabs 15.7% (3 pm – 9 pm on the 10th)
- South-East Asia 11.65% (7 pm – 1 am on the 10th)
- South Asia 27.62% (10 pm – 4 am on the 10th)
- Iran 3.4% (11 pm – 5 am in the 10th)
- TEAA 9.28% (1 pm – 7 pm on the 10th)
- Locals 24.03% (7 am on the 10th – 1 pm on the 11th)
- Arabic Gulf 1.21% (12 pm – 6 pm on the 11th)

The peaks or potentially congestion-generating periods may occur when multiple groups are allowed to enter the GM at the same time.

Upon their arrival, pilgrims are allocated one of the five main gates of the GM, with the percentage allocations in the model:

- King Abdullah gate 10%;
- Al-Marwah gate 10%;
- Al-Fatah gate 15%;
- Al-Umrah gate 15%;
- King Fahad gate 20%;
- King Abdullaziz gate 30%.

Before performing the Tawaf, the pilgrims queue at their allocated gate (**FIGURE 5-E**. Once they are admitted, they walk through the gate until reaching the Tawaf area, represented by Activity blocks (**FIGURE 6-A**). Tawaf is performed at one of the five levels, depending on the entrance allocation (**FIGURE 6-B**). The walking duration is calculated using *Equation blocks* (see **FIGURE 6-C**) and considers the distance from the gates to the Tawaf ritual areas (see **TABLE 16** in the Appendix). An example calculation is given below in [**EQUATION 1**], where ReduceSpeed (Age) and Tired (Fatigue) are factors that reduce the walking speed depending on the Age (and thus fitness) and fatigue level of the pilgrim. We have assumed that in the case of an incident, the walking time will double.

Entering from King Abdulaziz Gate (d=190 m)	Equation (time in min)

	if(Incident == 0)
	$Walktime = \frac{Distance \times \frac{1}{60}}{[\text{Speed} \times \text{ReduceSpeed(Age)} \times Tired(Fatigue)]}$
	Else
	$Walktime = \frac{Distance \times \frac{1}{60}}{2[\text{Speed} \times \text{ReduceSpeed(Age)} \times Tired(Fatigue)]}$

EQUATION 1

After arriving to the Tawaf areas, pilgrims may need to queue and face a delay as they merge with the people already performing Tawaf (**FIGURE 6-B**). A different equation block is used to calculate the duration of circumambulation, depending on the distance from the Ka'aba and level where it is performed, as well as the congestion conditions (**FIGURE 6-D**). After pilgrims finish Tawaf, they walk to the Sayee area (**FIGURE 6-E**). The walking duration is calculated in a similar manner to **EQUATION 1**.

Pilgrims may again queue and be delayed while joining other pilgrims performing the Sayee ritual (**FIGURE 7-A**). Completing the Sayee marks the end of rituals in the Grand Mosque and pilgrims exit the mosque through one of the gates. This is represented in the simulation by using the Exiting activities (**FIGURE 7-B and C**). Equation blocks are also used to calculate the duration of Sayee, accounting for the distance between the two hills and the walking time to exit as a function of the gate (see **EQUATION 1**). The Plotter Block (**FIGURE 7-D** provides the cumulative count of pilgrims completing both rituals over time (models made available in the institution repository).

The initial results of the simulation indicate that it takes 30 hours for the 12,000 groups (3,000,000 pilgrims) to complete both the Tawaf and Sayee rituals.

V. SIMULATION RESULTS

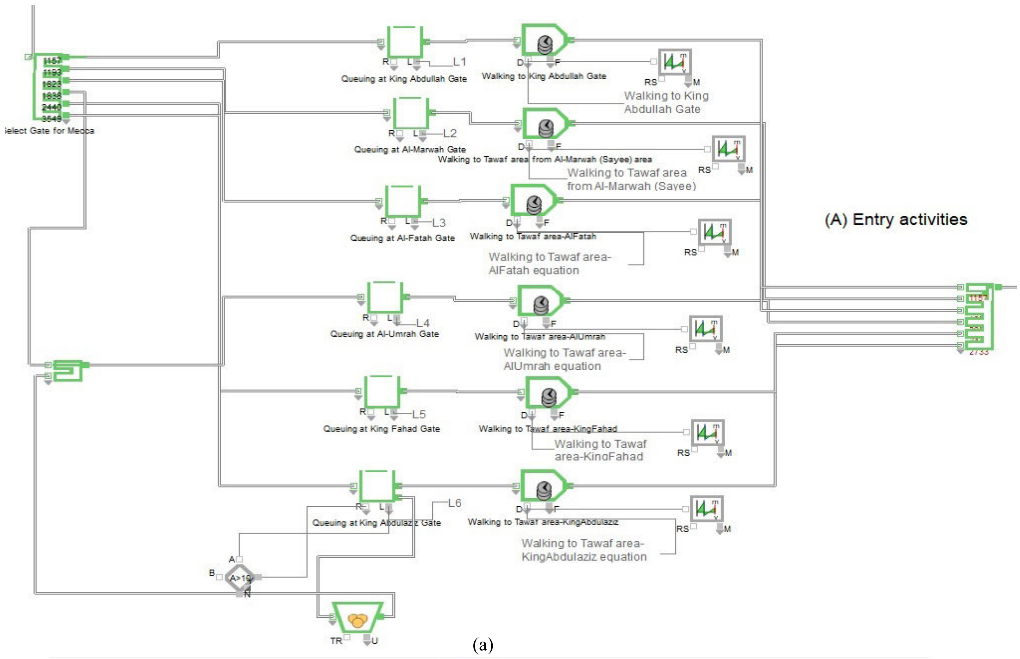
The model was run 30 times and the results were compared against statistics based on the real data (**TABLES 3, 4 and 5**). The inputs were stochastic and triangular distributions were assumed for activity durations; this means that the results are also stochastic. The use of triangular distributions is a potential limitation; further research could compare with other types of distributions for durations.

A. MODEL VALIDATION

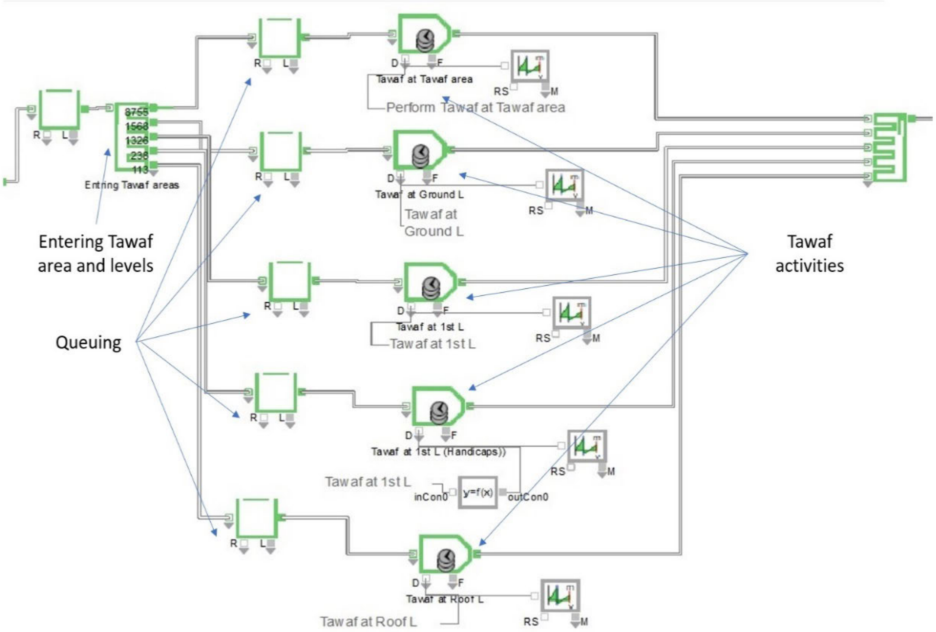
In 2019, a total of 2.6 million pilgrims performed Hajj, while our model admitted 3 million pilgrims. Nonetheless, the simulation results compare very well with the real data. The similarities indicate some potential reserve capacity in the system.

Table 3 shows the statistics for entering and exiting activities. The simulation results for the percentage of pilgrims entering through each gate matches closely with real data. Similarly, the actual walking times from the gates to Tawaf on entry, and to the exit gates on completing Sayee, show no statistically significant differences between simulation results and real data.

Table 4 and **Table 5** provide the percentage of pilgrims and durations for Tawaf and Sayee respectively. The differences between the simulations and real data for the percentage of pilgrims by gate and levels are under 1%, giving confidence in the veracity of the model. The LoS at Tawaf area and the Ground level of Sayee confirm that they are the most crowded areas, which could result in crowd incidents. From **Table 4**, at peak times the Tawaf area records an LoS of 6 p/m^2. The LoS for GL, L1 and roof level are lower, with a maximum of 2 pilgrims/m^2 at peak time. In addition, Tawaf durations show an average of 45 min at the Tawaf area, 42 min at GL, 48 min at L1 (duration of going to the next level is included in the models), 40 min at L1 MR and finally 55 min at the roof level. The General Presidency of The Affairs of The Grand Mosque and The Prophet's Mosque (2019) [62] provides allocation by levels for Sayee (**Table 5**). Our results indicate slightly shorter average times and better LoS, even with the larger number of pilgrims for 2019 (three million). The model closely mirrors the percentages of pilgrims undertaking the Sayee ritual at various levels. The longest times for performing Sayee are at levels 2 and 3 (on average 69 min). The most crowded area is the Ground level (6 p/m^2 at peak times), as this level accommodates nearly 60% of the pilgrims. The LoS is under 2 pilgrims/m^2 at peak times for Basement level and L1 (**Table 5**). The lower durations for the activities and better level of service suggest potential reserves of capacity in the system, able to accommodate over 2.6 million pilgrims.



(a)



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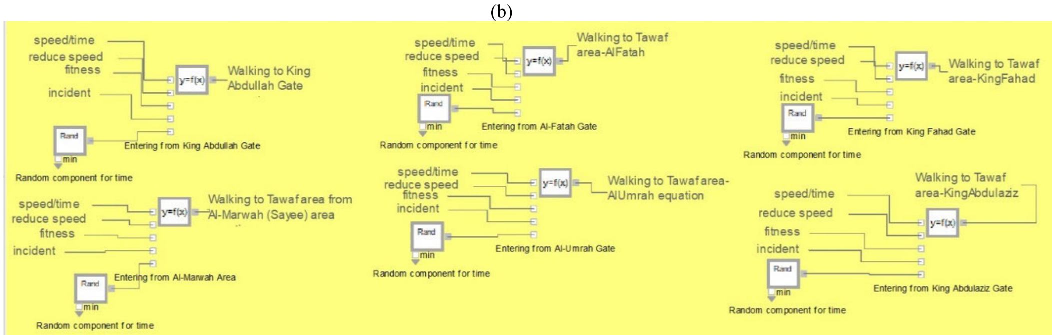
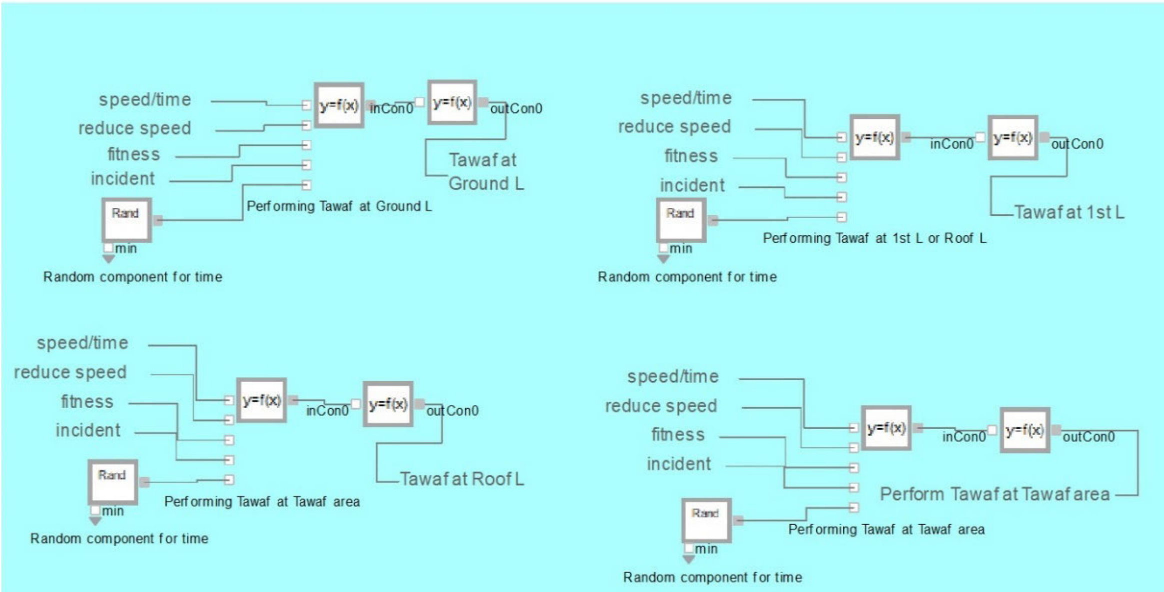
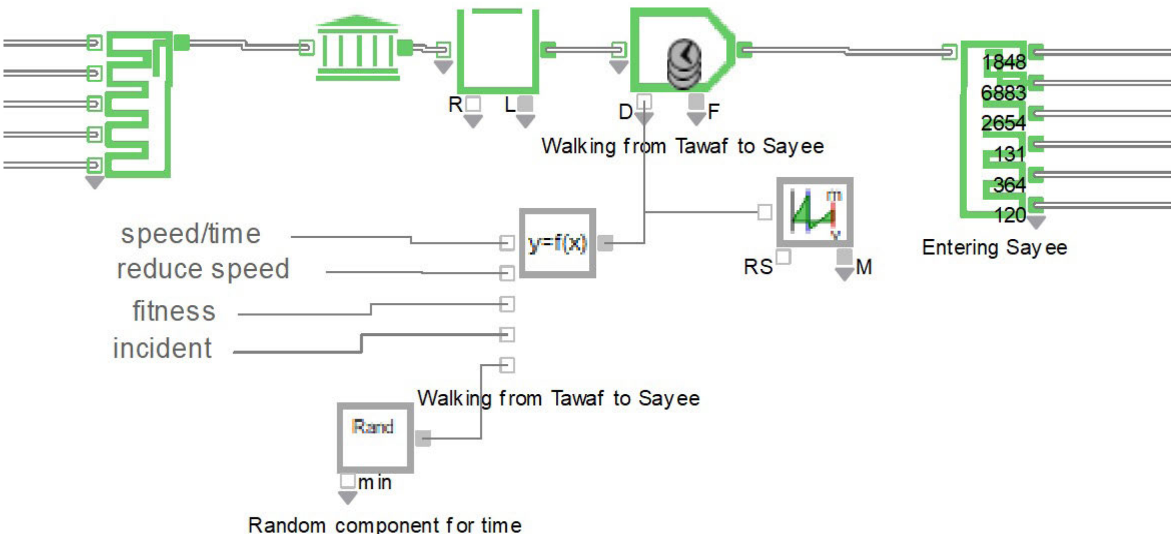


(c)

FIGURE 6. A: Entry activities. B: Tawaf activities. C: Entry equations. D: Tawaf equations. E: Walking activity from Tawaf to Sayee.



(d)



(e)

FIGURE 6. ***(Continued.)*** **A: Entry activities. B: Tawaf activities. C: Entry equations. D: Tawaf equations. E: Walking activity from Tawaf to Sayee.**

B. TAWAF AND SAYEE SCENARIOS

Problems due to overcrowding at Hajj sites may be contained and crowd incidents could be prevented by efficient crowd management, including sufficient prior planning through crowd modelling and simulation, infrastructure improvements, deployment of more security officers and better use of information technology [19].

Currently, Hajj evacuation procedures are planned and carried out by the Saudi Civil Defence (SCD) [63]. SCD trains and prepares more than 18,000 officers to execute evacuation procedures, using more than 3,000 devices and sophisticated pieces of equipment. They have developed more than 13 possible hazard scenarios for Hajj events, including extreme weather conditions (high temperatures, rain, wind, storm and floods), dangers at construction sites (e.g., mosque expansion), fires, falling rocks and crowd hazards.

In this study, we examine conditions for operation changes without incidents [Sections (I) to (V)] and for more likely hazard situations such as extreme heat or storms, which may require halting proceedings, including some rituals, or movement between sites [Section (VI)].

The scenarios in Table 6 were tested to estimate their effects on the LoS, as well as the average ritual activity durations and the average queue building at Tawaf and Sayee. These methods could be used as new strategical management options for the event. In addition, all Tawaf and Sayee (normal and evacuation) scenarios were designed and developed according to the Grand Mosque's

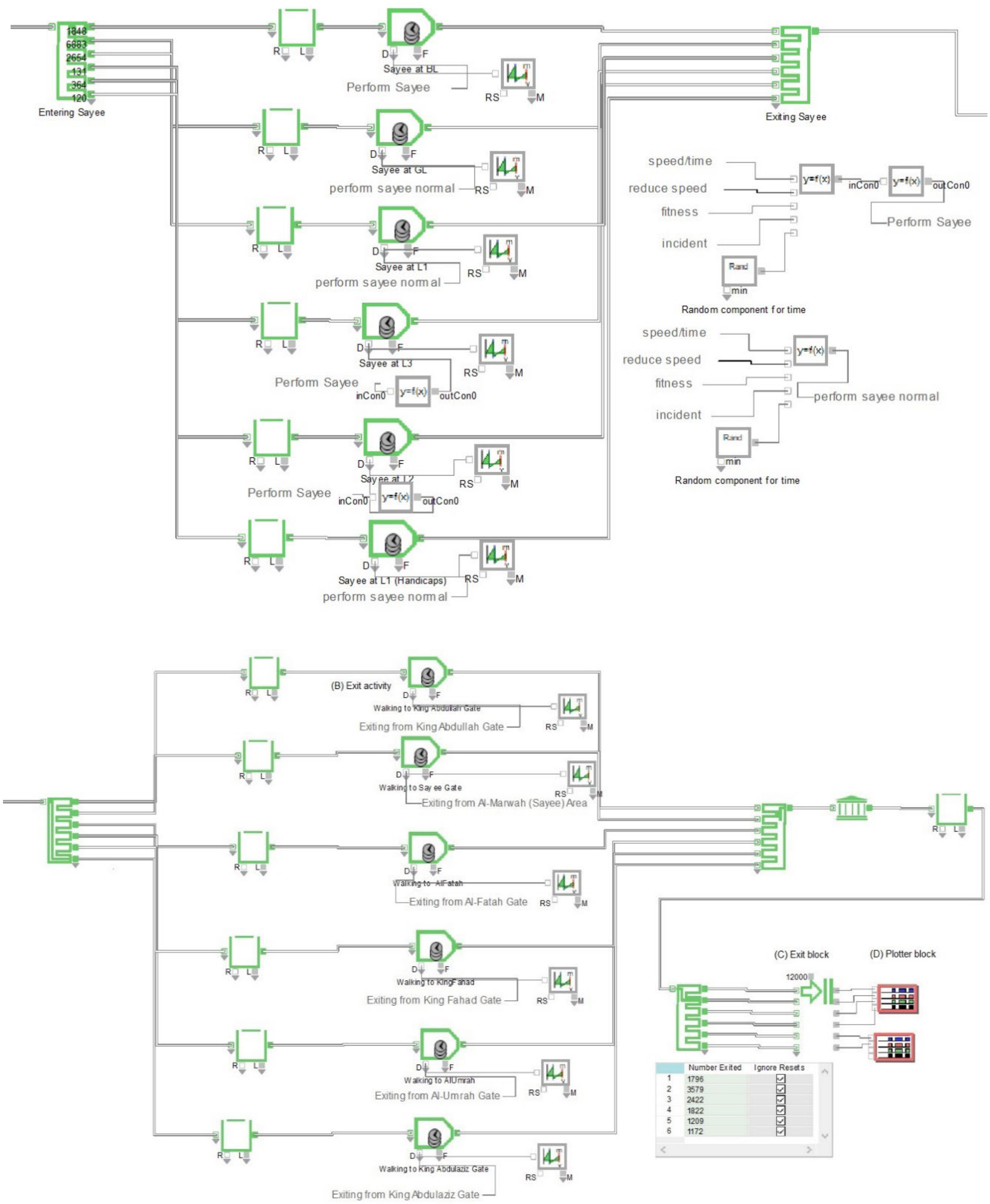


FIGURE 7. (A) Sayee activities and equations. (B) Exit activities, (C) Exit Blocks, (D) Plotter Blocks.

infrastructure including the new building of the King Abdullah expansion (see **FIGURE 3**). All these scenarios were replicated 30 times.

1) DEVELOPING TAWAF AND SAYEE SCENARIOS

Table 6 describes the scenarios we implemented in the Tawaf and Sayee model.

2) INDIVIDUAL SCENARIOS FOR ONE-WAY SENSITIVITY ANALYSIS

In these scenarios, the percentage allocation of pilgrims was changed only at one stage—entry, Tawaf, Sayee, or exit of the model at a time, while the remaining areas used the allocations of the original model. The results indicate that changes in the percentage allocations to gates for entry/exit

TABLE 3. Validation of arrivals and exit (statistics).

Main Gates	Entering Activity (Average over 30 hours)			Exiting Activity (Average over 30 hours)		
	Real Data 2019 (%) (*)	Sim. results (average throughput %)	Diff. (%)	Real Data 2019 (%)	Sim. results (average throughput %)	Diff. (%)
King Abdulaziz	**30**	30.26	0.26	**10**	10.80	0.80
King Fahad	**20**	20.57	0.57	**10**	9.57	-0.43
Al-Umrah	**15**	14.65	-0.35	**15**	15.38	0.38
Al-Fatah	**15**	15.10	0.10	**20**	19.50	-0.50
Al-Marwah (Sayee)	**10**	9.36	-0.64	**30**	29.85	-0.15
King Abdullah	**10**	10.06	0.06	**15**	14.90	-0.10
Main gates	**Average walking time to Tawaf (min) (**)**	**Avg. Sim. walking time to Tawaf (min)**	**Diff. (sec)**	**Avg. walking time to main gates (min)**	**Avg. Sim. walking time to main gates (min)**	**Diff. (sec)**
King Abdulaziz	3	2.88	-7	9	8.9	-6
King Fahad	5	4.82	-11	10	9.63	-22
Al-Umrah	4	3.85	-9	7	6.75	-15
Al-Fatah	5	4.82	-11	3	2.88	-7
Al-Marwah (Sayee)	8	7.72	-7	1	0.97	-2
King Abdullah	8	7.07	-20	5	4.82	-11

Note1: Sourced from: (*) data from the lead author, while (**) Avg Walking time to Tawaf (min) (The General Presidency of The Affairs of The Grand Mosque and The Prophet's Mosque, 2020) [59]
Note 2: The selection of the gate is based on the geographical location (the closest gate to enter Tawaf is the furthest from Sayee site).
Note 3: Simulation results represent Avg. of 30 simulation runs.

TABLE 4. Tawaf Activity - Validation.

	Real Data 2019	Sim. results	Diff.	Real Data 2019	Sim. Results (min)	Diff. (above 1h) (min)	Real Data 2019	Sim. results
	Percentages of pilgrims/30h (%) (*)			Duration of activity (**)			LoS pilgrims at peak times (p/m^2) (*)	
Tawaf area	**73.2**	72.56	-0.64	1 – 3 hours (**)	45.72	-14.28	4-8	6
Ground level (GL)	**12.7**	13.57	0.87	Normal situation: 15-20 min	42.18	-17.82	1-8	2
Level 1 (L1)	**11.1**	11.07	-0.03	Crowd situation: 50 min (***)	48.2	-11.80	1-8	2
Mobility Reduced (MR) restriction at L1	**2**	1.9	-0.10		40.0	-20.00	1-2	1
Roof level	**1**	0.9	-0.1		55.43	-4.57	1-8	1

Note: Sources: * Tawaf distribution (The General Presidency of The Affairs of The Grand Mosque and The Prophet's Mosque, 2019)][60]; ** Alshammari and Mikler (2015) [61]; *** Hajj and Umrah Planner (2019) [55]

or Sayee areas do not affect the overall duration of the Tawaf and Sayee rituals (within 30 hours). However, the model is sensitive to the percentage allocation for Tawaf areas and yields the poorest LoS when Tawaf area is closed. A multiple regression model for these scenarios with the number of pilgrims completing the rituals in 30h showed a significant effect of closing areas, as well of the age distribution of the pilgrims, but not of the level of fatigue on (R^2-adj = 0.77, see **Table 7**).

The regression model results confirm that lower numbers of pilgrims can be accommodated when the Mataf area is closed and that similar numbers of pilgrims are completing

TABLE 5. Sayee Activity - Validation.

	Real Data 2019	Sim. results	Diff.	Real Data 2019	Sim. Results (min)	Diff. (above 1h) (min)	Real Data 2019	Sim. results
	Percentages of pilgrims/30h (%) (*)			Duration of activity (**)			LoS pilgrims at peak times (p/m^2) (*)	
Basement level (BL)	**15.5**	15.24	-0.26	1 – 3 hours (**) Normal situation: 15-20 min Crowd situation: 35/40 min (***)	55.33	-4.67	1-4	2
GL	**57.5**	57.57	0.07		44.28	-15.72	4-8	6
L1	**22**	22.28	0.28		44.28	-15.72	1-4	2
Mobility Reduced (MR) restriction at L1	**1**	0.97	-0.03		44.28	-15.72	1-2	1
L2	**3**	2.84	-0.16		69.18	9.18	1-4	1
L3	**1**	1.1	-0.1		69.18	9.18	1-4	1

Note: * Sayee distribution (The General Presidency of The Affairs of The Grand Mosque and The Prophet's Mosque, 2019) [62];
** Alshammari and Mikler (2015) [61]; *** Hajj and Umrah Planner (2019) [55]

TABLE 6. Tawaf and Sayee scenarios.

Tawaf and Sayee scenarios	**Implementation**
Change the allocations for entering and exiting from the main gates (please refer to Table 3, columns 3 and 6)	Increasing, decreasing or meeting the allocations. For example: • Entering and exiting from only five gates • Closing the nearest entrance gate to Tawaf area (King Abdulaziz gate) • Closing the nearest exit gate from Sayee area (Al-Marwah gate)
Increasing or decreasing the pilgrim numbers at various Tawaf areas (please refer to Table 4, column 2)	Increasing, decreasing or meeting the allocations for the five areas. For example, reducing the number of pilgrims in Tawaf area and directing them to areas GL, 1st and roof levels, to avoid crowdedness at the Tawaf area (less than 6-8 p/m^2).
Increasing or decreasing the pilgrim numbers at various Sayee areas (please refer to Table 5, column 2)	Increasing, decreasing or meeting the allocations for the Sayee areas). For example, directing pilgrims from GL to BL, 1st, 2nd and 3rd levels, to avoid crowdedness at the Tawaf area (less than 6-8 p/m^2).
Allocating each group to a certain gate	Each group will enter GM from a certain assigned gate (not randomly), with large groups entering from the gates nearest to Tawaf.
Emergency evacuations from Tawaf and Sayee areas	Choose: • Nearest exits for evacuation • Least crowded/ Guided exits (reneging queue) *

* Suggested by Mohamad et al. (2013) [64]. In the less crowded/guided exits strategy, the pilgrims will be evacuated using visible exits guided by Hajj officials, which they have better knowledge about The Grand Mosque main entrances and exits.

Sayee at each level. Note that speed is not significant in the regression model since Speed and Age (dummy variable) are highly correlated. The main results of these scenarios are presented in **TABLE 8**.

3) MIXED SCENARIOS

A total of 110 mixed scenarios, where allocations were changed simultaneously in two or more areas, were developed as follows.

TABLE 7. Regression results (sensitivity analysis).

	B	Beta	t	Sig.	VIF
(Constant)	6,358.598		5.245	0	
Age dummy (over 50)	-1,741.956	-0.085	-1.688	0.092	4.019
Speed (m/s)	394.741	0.034	0.656	0.512	4.235
Tawaf GL	-4,647.51	-0.313	-8.844	0	1.994
Tawaf L1	-9,134.81	-0.626	-16.468	0	2.3
Tawaf MR L1	10,034.88	0.036	1.159	0.247	1.566
Tawaf Roof	-7,073.49	-0.503	-12.228	0	2.689
Sayee basement	6,918.741	0.449	8.743	0	4.206
Sayee GL	5,930.995	0.44	10.404	0	2.843
Sayee L1	6,225.335	0.404	9.002	0	3.209
Sayee MR L1	6,530.219	0.089	3.155	0.002	1.255
Sayee L3	7,123.877	0.163	5.487	0	1.402

- Changing the percentages allocations from 30% to 80% at all Tawaf and Sayee areas;
- Focusing on the most critical areas preferred by pilgrims and combining allocations (e.g., Tawaf area with Sayee GL, Tawaf GL with Sayee L1, Tawaf L1 with Sayee BL and Tawaf Roof L with Sayee L2);
- Changing pilgrim percentages at the King Abdulaziz (KAz.) entry gate, which is the closest gate to Tawaf levels;
- Changing pilgrim percentages at Al-Marwah exit gate, which is the closest gate to exit.

The simulation scenarios were categorised into three groups based on their results: scenarios that simulated all pilgrim groups within the simulation time (30 hours); scenarios that simulated between 9,000 and 12,000 groups; and scenarios that simulated less than 9,000 groups. Some important observations from the results of these scenarios are summarised below (for more details, the results can be found at UWA repository [2] and all the Grand Mosque main gates leading to Tawaf, including King Abdullah Gate were tested in the scenarios).

- Closure of Tawaf area, with the ritual performed at other levels, or underutilising the Tawaf area has the most negative impact on the completion of the rituals (only about 75% of the pilgrim groups completed the rituals within 30 hours).
- When critical gates to Tawaf area and Sayee were closed, delays occurred in completing the rituals and in evacuation.
- When Tawaf area was closed or received 20% to 40% of pilgrim groups, 9,000 to 11,000 groups completed the rituals within 30 hours.
- When Tawaf area was closed together with Sayee L3, only 5,000 to 9,000 groups completed the rituals within 30 hours.
- When Tawaf GL and Roof level were closed together with three exit gates, less than 10,000 groups completed the rituals within 30 hours.
- When two Sayee levels and two exit gates were closed, 9,000 pilgrim groups completed the rituals within 30 hours.
- When Tawaf area and Sayee GL received 40% to 60%, but two levels from each area were closed, up to 10,000 groups completed the rituals within 30 hours.
- If the proportion of pilgrims over 50 years of age increases, this significantly increases the duration of the rituals.

4) SIMULTANEOUS CHANGE OF TAWAF AND SAYEE SCENARIOS

Other scenarios were developed by simultaneously changing the percentages of pilgrim group at selected combinations of Tawaf and Sayee areas, but not at the gates. The changes were made sequentially, allocating from 0% to 80%, in steps of 10%. Table 9 shows the average time of Tawaf and Sayee rituals in the selected areas, as well as the total number of pilgrim groups completing the rituals in 30 hours. The poorest results, unsurprisingly, occur when multiple areas are closed or when the utilisation of the infrastructure/resources is unbalanced, primarily over-utilisation of the GL Tawaf and L1 and L2 Sayee areas. In contrast, judicious allocation of groups to the areas, proportionate to their capacities, leads to a satisfactory completion of the rituals within the planned time, while ensuring good LoS (less than 4 pilgrims/m^2). Closing the roof area of Tawaf and levels 2 and 3 Sayee has little impact on the number of pilgrims completing the rituals, but will increase crowding and LoS may exceed 4-5 pilgrims/m^2 in the adjacent areas. The results also highlight that Sayee ritual is generally longer than the Tawaf, reflecting the distance pilgrims require to cover between the two hills.

[2] https://cloudstor.aarnet.edu.au/plus/s/ZNprMWzZqNULBYY

5) ALLOCATION OF GATES TO PILGRIM GROUPS

Guided results of the mixed scenarios (Section IV) and by previous scholarly work, we examined scenarios in which pilgrim groups were assigned to a specific entry gate, depending on their bus stop locations around the Grand Mosque: SA to King Abdulaziz gate (K.Az.); Locals to King Fahad gate (K.F.); Arabs to Al-Umrah gate (U); SEA and Iran to Al-Fatah gate (F); Africa and Arabic Gulf to Al-Marwah gate (M) and TEAA to King Abdullah gate (K.A.) (see **FIGURE 8**). All pilgrim groups completed the rituals in 1,550 minutes, significantly less (138 minutes) from the original model where pilgrim groups enter randomly (1,688 min). Together with scheduling, this managerial strategy could lead to big improvements in completion times.

6) EVACUATION SCENARIOS

Cuesta *et al.* [65] mentioned three possible approaches when developing new scenarios for evacuation models: use of legacy models, improving current models or developing new evacuation models. Our approach was using legacy models, testing evacuation scenarios developed previously, then compare the results of these previous studies to ours, considering the differences in the infrastructure of evacuation scenarios. In addition, the evacuation scenarios can be categorised depending on how human movement is incorporated, either as flow-based, CA, ABM and activity-based model; or by considering the level of aggregation (macro-, micro-, and effect based) [65]. Our research approach fits the activity-based, macro-level description, offering insights on the managerial solutions potentially applicable to Hajj.

A few evacuation scenarios were developed to analyse how long it takes for the pilgrim groups to be evacuated from the four main areas of the GM (Tawaf, Sayee, transition between Tawaf-Sayee areas and the main exits), during their rituals. Additional blocks were added to the simulation model to depict pilgrim movement to the nearest gates instead of continuing their progression through the rituals. The new evacuation (Activity blocks) in each area were associated with Equation blocks specifying the walking times to the existing gates.

As indicated in Section IV (A), six big entry gates are connected to the Tawaf area and used as exits after the Sayee. However, in the evacuation model, all 179 gates were dynamically allocated to various pilgrim groups depending on the numbers and locations of the pilgrims at the time of evacuation.

FIGURE 9 shows the total number of groups of pilgrims within the main areas of Tawaf, Sayee, in transit between Tawaf-Sayee, their totals, and the cumulative number of groups that had exited the GM, over time. The chart is also indicative of the time at which pilgrims perform Tawaf and Sayee, and when they reach the highest numbers, based on the arrivals. As expected, the highest number of pilgrims in Tawaf seems to be recorded around 12 hours after the official time of the start of the ritual, and after 14 hours for Sayee.

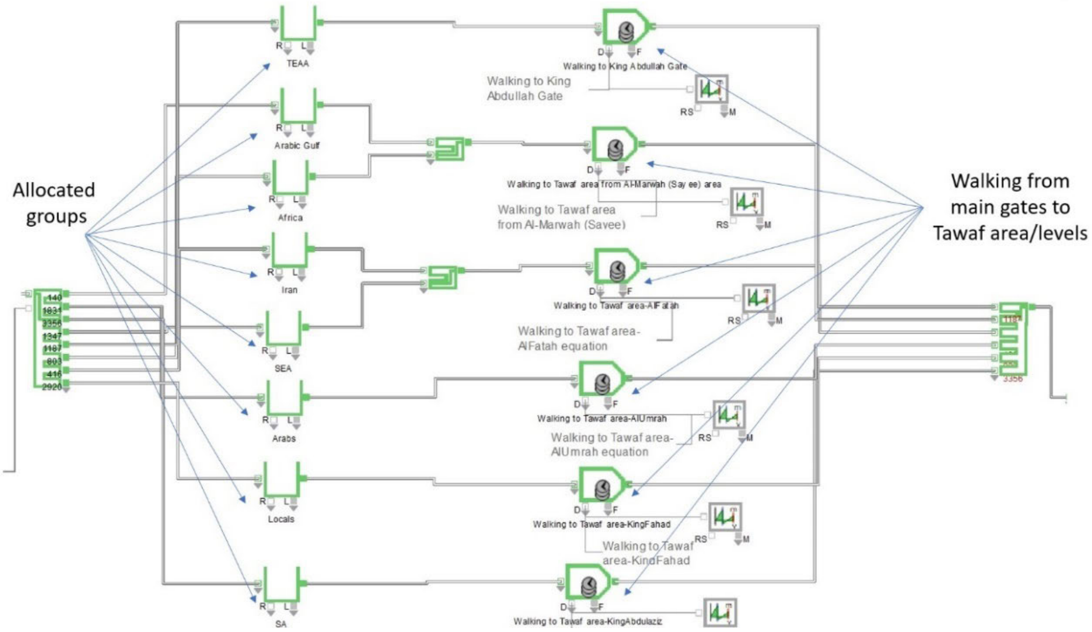


FIGURE 8. Allocated groups.

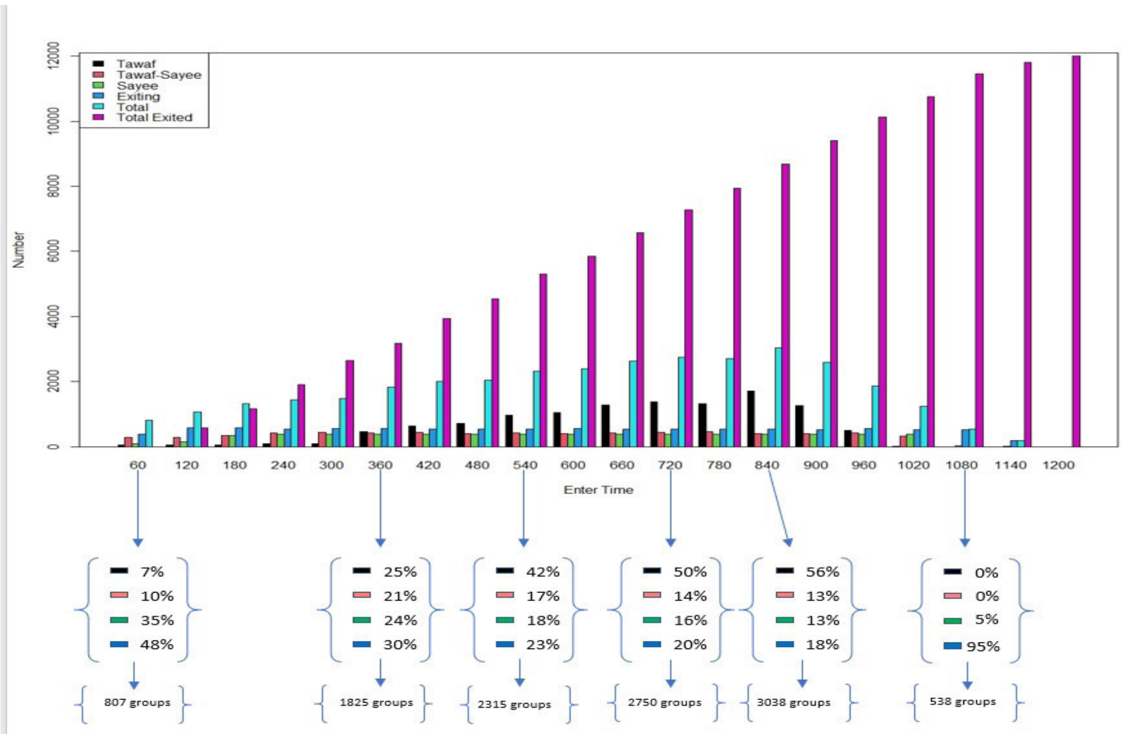


FIGURE 9. Total number of groups of pilgrims at areas of Tawaf, Sayee, in transit between Tawaf-Sayee and the cumulative number of groups that had exited the GM, over time.

This is the critical time for evacuation and likely to lead to longest evacuation times, given that more than a quarter of the pilgrims are in the Tawaf-Sayee areas performing their rituals. At this time, less than 2,000 groups were yet to commence their rituals. In an evacuation situation, they will not be entering the GM but will need to disperse, to allow the pilgrims inside the GM to exit.

The chart is complemented by details of the split of the number of groups of pilgrims in each area during the evacuation at 60, 360, 540, 720, 840 and 1,080 minutes. After

TABLE 8. Allocations for the Tawaf and Sayee scenarios.

<table>
<tr><th colspan="6">Entry/Exit Gates (%)</th><th colspan="5">Tawaf levels (%)</th><th colspan="6">Sayee levels (%)</th><th rowspan="2">Completion (#Groups out of 12,000)</th></tr>
<tr><th>K. A.</th><th>M</th><th>F</th><th>U</th><th>K. F.</th><th>K.Az</th><th>Tawaf Area</th><th>GL</th><th>L1</th><th>L1 (MR*)</th><th>Roof L</th><th>BL</th><th>GL</th><th>L1</th><th>L1 (MR*)</th><th>L2</th><th>L3</th></tr>
<tr><td colspan="18">Entry gates allocations</td></tr>
<tr><td rowspan="3">10</td><td rowspan="3">10</td><td rowspan="3">20</td><td>30</td><td>30</td><td>0</td><td colspan="11" rowspan="5">No changes from 2019 in Tawaf, Sayee allocations and exit gates</td><td rowspan="5">12,000</td></tr>
<tr><td rowspan="2">20</td><td>30</td><td>10</td></tr>
<tr><td>20</td><td>20</td></tr>
<tr><td>16</td><td>16</td><td>17</td><td>17</td><td>17</td><td>17</td></tr>
<tr><td>0</td><td>10</td><td>15</td><td>15</td><td>30</td><td>30</td></tr>
<tr><td colspan="18">Tawaf level allocations</td></tr>
<tr><td colspan="6" rowspan="6">No changes from 2019 allocations to entry and exit gates</td><td>0</td><td>35</td><td>35</td><td rowspan="6">1</td><td>29</td><td colspan="6" rowspan="6">No changes from 2019 allocations to Sayee levels</td><td>9,151</td></tr>
<tr><td>30</td><td>24</td><td>25</td><td>20</td><td rowspan="4">12,000</td></tr>
<tr><td>40</td><td>20</td><td>20</td><td rowspan="2">19</td></tr>
<tr><td>50</td><td>15</td><td>15</td></tr>
<tr><td>60</td><td>15</td><td>15</td><td>9</td></tr>
<tr><td>25</td><td>25</td><td>25</td><td>24</td><td>10,836</td></tr>
<tr><td colspan="18">Sayee level allocations</td></tr>
<tr><td colspan="11" rowspan="6">No changes from 2019 allocations in gates allocations for entry, exit and Tawaf levels</td><td rowspan="5">20</td><td>0</td><td>30</td><td rowspan="6">1</td><td>29</td><td>20</td><td rowspan="6">12,000</td></tr>
<tr><td>30</td><td rowspan="4">20</td><td>15</td><td>14</td></tr>
<tr><td>40</td><td>10</td><td>9</td></tr>
<tr><td>50</td><td>5</td><td>4</td></tr>
<tr><td>20</td><td>20</td><td>19</td></tr>
<tr><td>15.50</td><td>57.5</td><td>22</td><td>4</td><td>0</td></tr>
<tr><td colspan="18">Exit gates allocations</td></tr>
<tr><td rowspan="3">20</td><td>0</td><td>30</td><td>30</td><td rowspan="3">10</td><td rowspan="3">10</td><td colspan="11" rowspan="6">No changes from real data 2019 in Tawaf, Sayee allocations and entry gates</td><td rowspan="6">12,000</td></tr>
<tr><td>10</td><td>25</td><td>25</td></tr>
<tr><td>20</td><td>20</td><td>20</td></tr>
<tr><td>10</td><td>30</td><td>15</td><td>15</td><td>15</td><td>15</td></tr>
<tr><td>16</td><td>16</td><td>17</td><td>17</td><td>17</td><td>17</td></tr>
<tr><td>0</td><td>30</td><td>30</td><td>20</td><td>10</td><td>10</td></tr>
</table>

■ Gate or level is closed. K.A. = King Abdullah, M = Al Marwah, F = Al-Fatah, U=Al-Umrah, K.F. = King Fahad, K.Az = King Abdul Az

60 minutes, 7% of the pilgrims are in Tawaf, while most groups are performing Sayee and exiting. After six hours (360 minutes) since the start of the simulation, pilgrim groups are spread evenly across all GM areas. After nine hours (540 minutes), Tawaf area recorded the largest proportion of groups of pilgrims within the GM. This continues to increase steadily, so that after 12-16 hours (720-840 minutes), 50% to 56% of the groups are performing Tawaf. After this time, most pilgrims within the GM are expected to complete Sayee, before all the pilgrims finish their rituals and exit the system. The simulation was run for 20 hours, with 95% of the groups exiting the system within 18 hours (1,080 minutes).

VI. DISCUSSION OF RESULTS

The results of the one-way sensitivity analysis (**TABLE 8**) show that all pilgrim groups completed the rituals except when the Tawaf area is underutilised (<30%) or closed. When the main Tawaf area, preferred by the pilgrims, was closed, only 9,000 groups out of 12,000 groups could be accommodated. In the scenario with equal percentages at all Tawaf levels (except for the handicap mobility area at level 1), only 10,836 groups completed the rituals in the allotted time. Queues, building up at all Tawaf levels, required more time for finishing the ritual. When the Tawaf area accommodates 30-50% of pilgrims, all pilgrims could complete the rituals in 30 hours, with some queues built at the Tawaf area and Sayee GL (the most critical Sayee area). Closure of other areas (gates, Sayee GL or L3) did not impact the completion of the rituals within 30 hours. Our results also show that when the Tawaf area and the Sayee GL receive up to 60% of the pilgrims (LoS = 5 p/m^2) there are no queues in the system. Therefore, these scenarios could potentially offer managerial

TABLE 9. Simultaneous Tawaf and Sayee scenarios and results.

Scenario No.	Tawaf levels (%)					Sayee levels (%)						LoS in Tawaf area (pilgrims/m²)	LoS in Sayee GL area (pilgrims/m²)	Duration of Tawaf (mins)	Duration of Sayee (mins)	Completion (# Groups out of 12,000)
	Tawaf Area	GL	L1	L1 (MR)	Roof L	BL	GL	L1	L1 (MR)	L2	L3					
1	0	50	30	5	15	50	0	30	5	7	8	0	0	N/A	N/A	9,692
2	10	40	40	5	5	40	10	20	5	20	5	0.77	0.72	32.60	49.33	10,340
3	20	30	30	5	15	30	20	20	5	15	10	1.54	1.44			12,000
4	30	20	45	5	0	20	30	30	5	0	15	2.32	2.16			9,495
5	40	10	30	5	15	10	40	10	5	15	20	3.09	2.87			12,000
6	50	45	0	5	0	40	50	0	5	0	5	3.86	3.59			10,700
7	60	10	15	5	10	10	60	10	5	10	5	4.63	4.31			12,000
8	70	5	10	5	10	5	70	5	5	10	5	5.41	5.03			12,000
9	80	15	0	5	0	18	80	0	5	0	0	6.18	5.75			12,000
Scenario No.	Tawaf levels					Sayee levels						LoS in Tawaf GL (pilgrims/m²)	LoS in Sayee BL (pilgrims/m²)	Duration of Tawaf (mins)	Duration of Sayee (mins)	Completion (# Groups out of 12,000)
	Tawaf Area	GL	L1	L1 (MR)	Roof L	BL	GL	L1	L1 (MR)	L2	L3					
10	36	0	10	4	50	0	36	30	4	20	10	0	0	N/A	N/A	5,255
11	25	10	21	4	40	10	20	21	4	40	5	1.06	0.72	30.03	43.41	6,320
12	15	20	31	4	30	20	15	10	4	30	21	2.12	1.44			8,157
13	35	30	11	4	20	30	35	5	4	20	6	3.18	2.16			12,000
14	50	40	0	4	1	40	50	0	4	6	0	4.25	2.87			12,000
15	40	50	6	4	0	50	40	5	4	0	1	5.31	3.59			9,493
16	30	60	3	4	3	60	30	5	4	0	1	6.37	4.31			7,127
17	20	70	3	4	3	70	20	4	4	0	2	7.43	5.03			6,795
18	10	80	0	4	6	80	10	0	4	6	0	8.49	5.75			6,017
Scenario No.	Tawaf levels					Sayee levels						LoS in Tawaf L1 (pilgrims/m²)	LoS in Sayee L1 (pilgrims/m²)	Duration of Tawaf (mins)	Duration of Sayee (mins)	Completion (# Groups out of 12,000)
	Tawaf Area	GL	L1	L1 (MR)	Roof L	BL	GL	L1	L1 (MR)	L2	L3					
19	35	50	0	3	12	35	50	0	3	10	2	0	0	N/A	N/A	9571
20	25	40	10	3	22	25	40	10	3	5	17	1.21	0.72	42.90	45.30	9,844
21	35	30	20	3	12	35	30	20	3	5	7	2.42	1.44			12,000
22	0	20	30	3	47	0	20	30	3	47	0	3.63	2.16			5,722
23	0	10	40	3	47	0	10	40	3	20	27	4.85	2.87			5,449
24	10	0	50	3	37	10	0	50	3	3	7	6.06	3.59			7,104
25	7	0	60	3	30	7	0	60	3	20	10	7.27	4.31			7,037
26	6	1	70	3	20	6	1	70	3	10	10	8.48	5.03			6,071
27	1	6	80	3	10	1	6	80	3	5	5	9.69	5.75			5,326
Scenario No.	Tawaf levels					Sayee levels						LoS in Tawaf Roof L (pilgrims/m²)	in Sayee L2 (pilgrims/m²)	Duration of Tawaf (mins)	Duration of Sayee (mins)	Completion (# Groups out of 12,000)
	Tawaf Area	GL	L1	L1 (MR)	Roof L	BL	GL	L1	L1 (MR)	L2	L3					
28	50	20	28	2	0	50	15	15	2	0	18	0	0	N/A	N/A	12,000
29	40	30	18	2	10	40	30	10	2	10	8	1.21	0.72	55.25	61.67	12,000
30	30	20	28	2	20	30	20	20	2	20	8	2.42	1.44			12,000
31	20	30	18	2	30	20	30	15	2	30	3	3.63	2.16			12,000
32	8	50	0	2	40	10	50	0	2	40	8	4.85	2.87			8,289
33	8	40	0	2	50	20	10	0	2	50	18	6.06	3.59			6,121
34	38	0	0	2	60	30	0	0	2	60	8	7.27	4.31			4,582
35	28	0	0	2	70	8	10	5	2	70	5	8.48	5.03			4,503
36	18	0	0	2	80	18	0	0	0.02	80	0	9.69	5.75			3,649

Gate or level is closed | Scenario pattern | Acceptable | LoS Fair | LoS Unacceptable service levels

Note: LoS derived only for the tested area (in yellow). Capacities for Tawaf L1 and Roof level, and all the Sayee levels, are the same

methods in organising pilgrim movements inside the Grand Mosque. If the LoS needs to be maintained at less than $1p/m^2$, an anticipated requirement for physical distancing related to COVID-19, the number of pilgrims performing Hajj has to diminish accordingly. The entry gates have a direct impact on crowd build-up on Tawaf and Sayee levels. Some queues are generated at the Tawaf and Sayee GL, due to the changes in the entry percentages in the entry allocation scenarios. Increasing allocations to King Abdulaziz, Al-Marwah and King Abdullah gates decreases the waiting times, whereas the closure of any of these increases the waiting times. Given the follow-on effects of gate allocation on the upstream and downstream activities, gate allocation should be given priority in the planning of Hajj rituals in the Grand Mosque.

TABLE 10. Results of simultaneous Tawaf and Sayee scenarios.

Tawaf and Sayee levels	Pilgrim Percentages (%)								
	0	10	20	30	40	50	60	70	80
Tawaf area and Sayee GL	9692	10340	12000	9495	12000	10700	12000	12000	12000
Tawaf GL and Sayee BL	5255	6320	8157	12000	12000	9493	7127	6795	6017
Tawaf L1 and Sayee L1	9571	9844	12000	5722	5449	7104	7037	6071	5326
Tawaf Roof L and Sayee L2	12000	12000	12000	8289	6121	4582	4503	3649	3330

Acceptable results (LoS) Fair results (LoS) Unacceptable service level (queuing time)

The simulation results in the Mixed Scenarios [section (V-B-(3)], indicate that the allocation of pilgrims to areas proportional to their capacity is essential. Pilgrim percentages between 30% to 80% at Tawaf area and Sayee GL lead to better results and all groups completed the rituals. However, when the percentage allocations were increased to 60%, 70% and 80% at the remainder of Tawaf and Sayee levels, crowds built up and fewer pilgrims completed the rituals. On average, Tawaf lasts between 30 and 55 minutes, depending on the distribution of pilgrims by areas, and the Sayee ritual lasts between 40 and 60 minutes. In addition, closing one or two entry gates (while keeping all exit gates open) leads to fewer pilgrim groups (between 5,000 to 9,000 groups) completing the rituals. Therefore, closing entry gates is not an efficient managerial strategy in organising pilgrims when entering the GM or evacuating it.

Maintaining the gate allocation but changing the distribution in the Tawaf and Sayee areas (**Table 9**), gave similar results, confirming that underutilisation of the Tawaf or Sayee GL (< 10% of pilgrim groups) has a negative effect on completing the rituals (only 9,000 to 10,000 groups). However, when the utilisation is 20%, all pilgrims complete the activities. In the scenario 30% in Tawaf area and Sayee GL, more than 9,000 pilgrims (75%) completed the rituals, because the Tawaf Roof level and Sayee L2 were closed. Delays were recorded for the remaining 25% of the pilgrims crowding at these areas. The scenarios of 40%, 60%, 70% and 80% (No. 5, 7, 8 and 9) simulate all pilgrims efficiently, even though in the 80% scenario two levels were closed on both Tawaf and Sayee areas. The closures of these levels indicate that whenever the critical areas of Tawaf area and Sayee GL receive up to 80% (LoS = 6 p/ m^2), the rituals can be performed without many disruptions. Finally, in the 50% scenario, about 10,000 groups completed the rituals. The main reason is the delay due to closures of Tawaf L1 and roof levels and Sayee levels L1 and L2, which occurred again in the scenario with 80% in the Tawaf and Sayee GL. However, when these closures were associated with the 80% use of the Tawaf and Sayee GL, all groups were simulated within 30 hours.

Tawaf GL and Sayee BL are the next critical areas (scenarios no.10-18 in Table 9). In the scenarios of 0%, 10% and 20%, 5,000 to 8,000 groups of pilgrims (41-66%) complete the rituals. The delays appear from the crowds built on the Roof level and Sayee L2. However, in the 30% and 40% scenarios, all pilgrims complete the rituals, even though Tawaf L1 and Sayee L1 were closed. When the percentages in the Tawaf GL and Sayee BL increase over 50%, less than 9,500 pilgrim groups are simulated. Crowds are built at the same areas because the largest areas in Tawaf and Sayee received only 10% up to 30% of the total number of pilgrim groups.

Scenarios 19 to 27 (from **Table 9**) considered percentages from 0% to 80% in the Tawaf L1 and Sayee L1. Again, because the main Tawaf area and GL, as well as Sayee BL and GL were closed, only 5,326 to 7,104 groups completed the activities. These closures additionally lead to crowd building in these areas, especially when pilgrims' percentages were from 60% to 80%. On the other hand, when Tawaf L1 and Sayee L1 only received 20% of the pilgrims, this enabled all pilgrims to complete the rituals.

Finally, when the least preferred or accessible Tawaf and Sayee areas, Tawaf Roof level and Sayee L2, are increasingly being used, with the same pattern, accommodating pilgrims between 40 to 80%, queues appear and only 3,649 to 8,289 groups could complete the rituals within 30 hours. The crowded locations were Tawaf L1 and Sayee L1, as well as tested areas. Scenarios of 0 to 30% simulated all pilgrims, as the critical areas (Mataf and Sayee GL) accommodated 30 to 50% of pilgrim groups.

Table 10 provides a summary of the main results of the simultaneous Tawaf and Sayee scenarios [section (V-B-(4)] and the number of simulated pilgrims is given in relation to the percentage of pilgrims assigned to the area. The results confirm that allocating more than 30% of pilgrims to Tawaf L1 and Sayee L1, or to Tawaf Roof L and Sayee L2, is unwise, as less than 3/4 of the pilgrim groups can complete the rituals. The optimal allocation is when using Tawaf and Sayee GL according to their capacities and when distributing 30-40% of the pilgrims to the Tawaf GL and Sayee BL.

In terms of evacuation from the GM (**Table 11**), previous studies presented longer durations than obtained in this research. For example, studies reported 14 minutes from

TABLE 11. Comparison of evacuation results with previous studies.

Study	Duration of evacuation from Tawaf levels (min)				Duration of evacuation from Sayee levels (min)				
	Tawaf area	GL	L1	Roof L	BL	GL	L1	L2	L3
Halabi (2006) [36] (please see to Table 1, where different number of pilgrims are simulated [44,210; 277,938 pilgrims])	2.15	13.73	7.98	22.36	N/A				
Abdelghany et al. (2010) [34] (please see to Table 2, where different number of pilgrims are simulated [5,000; 25,000 pilgrims])	N/A				N/A	1st set 9.97 32.10 47.08 2nd set 20.62 19.32 18.88 5th set 16.6 18.6 16.1 21.0	N/A		
Mahmood et al. (2017) [[3]] [10,000 pilgrims]	7.4 4.0 3.1	N/A			N/A				
This study (3 million pilgrims)									
60 min	10.05	4.69	6.53	8.98	6.31	7.21	9.08	11.69	14.51
360 min	10.81	8.64	11.81	13.90	4.55	6.11	8.90	10.74	12.74
540 min	10.52	5.83	7.64	9.57	4.46	7.08	10.16	11.59	12.63
720 min	11.29	5.70	7.00	8.89	9.11	10.29	12.82	13.93	15.93
840 min	11.18	6.16	8.40	11.40	8.40	10.06	12.22	13.02	14.22
1080 min	N/A	N/A	N/A	N/A	6.70	8.87	9.95	10.86	13.15

TABLE 12. Number of evacuated groups in the evacuation model.

Evacuation time	No. of groups NOT entered the simulation	No. of evacuated groups				No. of groups finished and exited the simulation	Total groups No.	Total evacuation exits	LoS		Avg. No. of groups per gates
		Tawaf area and levels	Tawaf-Sayee area	Sayee levels	Exits				Tawaf	Sayee	
60 min	11,400	44	224	66	266	0	12,000	179	3.31	2.56	3.35
360 min	8,400	46	228	54	487	2,785			3.40	2.41	4.55
540 min	6,600	43	221	61	472	4,603			3.26	2.46	4.45
720 min	4,800	47	226	56	490	6,381			3.40	2.43	4.57
840 min	3,600	49	223	56	473	7,599			3.41	2.41	4.47
1,080 min	1,200	0	0	65	463	10,272			N/A	0.93	2.94

Note: Number of evacuated groups from Tawaf-Sayee (transit) area were spilt between Tawaf and Sayee levels for the calculation of LoS at Tawaf, Sayee and the Avg. number of groups exited from each gate.

Tawaf GL and 22 minutes from Tawaf Roof level [31], 47 minutes from Sayee GL [29] and 7 minutes from Tawaf area [3]. Our results from **Table 11** show shorter evacuation durations. We selected a discrete number of times when the evacuation may occur, at 60, 360, 540, 720, 840 and 1,080 minutes during the rituals. The evacuation from the Tawaf area takes between 10.05 to 11.18 min, from GL between 4.69 to 8.64 min, from L1 between 6.53 to 11.81 min, and from the Roof level between 8.89 to 13.90 min, according to the distances to the nearest exit gates. The evacuation durations from Sayee BL are between 4.46 to 9.11 min, from GL between 6.11 to 10.29 min, from L1 between 8.90 to 12.82 min, from L2 between 10.74 to 13.93 min and from L3 between 12.63 to 15.93 min.

To complete the insights on the effects of evacuation at various times during the Hajj rituals, **Table 12** shows the number of evacuated pilgrims from the Grand Mosque at the given times, from their locations during the evacuation process. The total number of groups at all times is 12,000 groups.

Additionally, all evacuated groups used all the Grand Mosque's exits (179 gates) in the evacuation simulation. **Table 12** shows that the maximum LoS is about 3.41 pilgrims/m^2 at Tawaf and 2.56 pilgrims/m^2 at Sayee. These figures are promising, indicating reduced chance of crowds building in various areas of the Grand Mosque. As Algahdi and Still [43] suggested, crowd density at max 4 people/m^2 is a safe limit for crowd flow. Therefore, pilgrims at Tawaf and Sayee are evacuated without any complications. The same observation can be made in relation to the number of groups evacuated from each of the 179 gates (including the gate of King Abdullah's new building). From **Table 12**, the maximum number of groups evacuated is about 4.55, which is equivalent to approximately 1,137 pilgrims per gate, regardless on the time when the evacuation is occurring.

VII. CONCLUSION AND FUTURE WORK

Hajj is the largest mass gathering event in the world. Mitigation of overcrowding at Hajj sites is one of the daunting tasks faced by Hajj officials. Prior planning to organise the movements of the pilgrims, especially for the Tawaf and Sayee rituals, is not only recommended for better use of resources, but also to avoid deleterious effects of emergency situations. While previous studies presented different approaches of Tawaf or Sayee management separately, an important contribution of this work is an integrated Tawaf and Sayee model with various scenarios, using the DES tool ''ExtendSim'' as a research method. Various scenarios were developed to offer different managerial options. The scenarios considered different aspects in pilgrim management at entrances and exits of the Grand Mosque, and Tawaf and Sayee rituals.

Without a micro-level description of physical structures and of individual entities or pilgrims, this study offers insights into the optimal allocations of pilgrims to control crowd density in the GM, in the most strained areas in terms of capacity, and on the conditions of evacuation (LoS, flow capacities, times to traverse or cross the GM towards exit gates). In addition, it shows that by scheduling the two rituals and an adequate allocation to the various levels of the Grand Mosque, there is potential for accommodating larger numbers of pilgrims within the same time window of 30 hours. For example, the average duration required for a number of four million pilgrims to complete both Tawaf and Sayee is 1,783 min (assuming current conditions and no critical incidents), which suggests reserves of capacity could be created through planning. Although our target was to simulate 3 million pilgrims, using the same conditions, the model could simulate up to 4 million pilgrims within the allotted 30 hours.

After validating the simulation model with the 2019 Hajj data, more than 200 distinct scenarios, manipulating a single factor or multiple factors, were examined.

The results show that distributing pilgrim groups according to the capacity achieves superior LoS, whereas closing entry gates, exit gates, and some Tawaf and Sayee levels will negatively affects LoS. The magnitude of these impacts depends on the allocation. Allocating more than 30% of the pilgrim groups to the upper levels of Tawaf and Sayee would result in queues and an LoS above 4 pilgrims/m^2. Another factor to consider is the age distribution of pilgrims, which affects the duration of rituals and movements between sites. On average, the Tawaf ritual lasts up to 55 min, whereas the Sayee up to 62 min, reflecting the distances pilgrims' traverse during rituals.

The simulation results confirm that the most critically high crowd density areas (yet preferred by pilgrims) are the Tawaf area (Mataf) and Sayee Ground Level (GL). As indicated, when these areas accommodated 30% to 80% of pilgrims, all pilgrims completed the rituals in a timely fashion. On the contrary, when other Tawaf and Sayee areas were assigned high percentages of pilgrims, the scenarios showed delays and inability to accommodate all pilgrim groups to complete the rituals within 30 hours. Therefore, it is recommended to distribute the pilgrims gradually, starting from the Tawaf and Sayee critical areas (Tawaf area and Sayee GL) followed by other levels. Another managerial method that could be considered in the organisation of the event is the allocation of each pilgrim group to a certain gate for entry and exit.

These findings create the prospect of more realistic strategies, which can be then further analysed at an individual pilgrim level. Currently, modelling the potential of panic, crowding behaviour (body movements, reactions) is impeded by treating pilgrims in groups with relatively homogeneous features and without considering emergent behaviour of pilgrims. However, the model presented here is part of a series of DES modelling the whole Hajj. Depending on the timing and location of emergency evacuation, procedures and consequences differ. In addition to identifying areas and pathways for evacuation response, the model showed that awareness of the exits and evacuation paths and training, as well as scheduling considering the physical agility of pilgrims, are critical factors that could ensure completing the evacuation in minimum times.

Consistent with Halabi [36] who alerted to the long duration of the processes, our results showed shorter evacuation times compared with other state of the art methods. Yet, this may be due to our meso-level treatment of the crowd and the 'locally optimised' decisions, considering natural flows from one part of the Grand Mosque to another, avoiding intersections of pedestrian routes. It is also recommended to apply better schedule planning regarding arriving and departing the Grand Mosque. For example, pilgrims who are well and fit (see **Table 14**) and can finish the rituals quickly, can be scheduled to arrive earlier, at the beginning of the Tawaf Al-ifadah day. Conversely, pilgrims less fit and who would require longer time in their ritual performance, can be scheduled to arrive later. This can be used as a managerial method in prior planning to organise the movements of the pilgrims, avoiding various pilgrim groups crossing each other and causing delays.

Unlike Abdelghany *et al.* [34] who explored the possibility that entities can decide which exit to choose during evacuation, in our model, we made the decision that groups are allocated evacuation exits depending on three factors: the nearest gates; further gates but within the same area; and using any available gates. However, we concur with Abdelghany *et al.* [34] that training pilgrims how to react in emergency situations is of paramount importance. This could be done either by receiving training before arrival or at least by training the group leaders, who have experience in performing Hajj rituals and are familiar with the facilities. Future work could develop normal and evacuation scenarios to test the organisation of the pilgrims during other Hajj rituals, at different locations.

APPENDIX – BLOCK AND INPUT DATA USED IN SIMULATION

See Table 13–16.

TABLE 13. ExtendSim Blocks Used in the Models [57], [66].

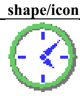
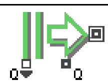
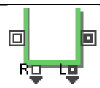
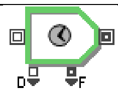
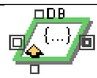
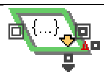
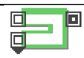
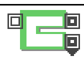
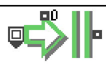
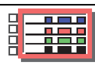
Block	Function	Block shape/icon
Executive Block	Controls the simulation timing and passing of the systems through the model. This block is placed on the left of all other blocks in the models. The main functions of this block it to schedule the events (system processes), control the simulation, allocate the items, manage the main attributes and other main settings.	
Create Block	Generates items (simulated pilgrims or transport modes) randomly or according to fixed schedules.	
Queue Block	Used as a holding area, where items (pilgrims or transport modes) queue up and wait to be processed. The queue releases the items based on their queuing settings.	
Activity Block	Simulates activity by delaying passing an item through the block in a certain amount of time, equivalent to the processing time of the real system.	
Set Block	Sets the properties of items that pass through the block.	
Get Blocks	Produces item properties from items that are passing through	
Select In Block	Merges the flow of the items from one process (input) to another process (output).	
Select Out Block	Separates the flow of items from one process (output) to another process (input).	
Exit Block	Passes items out of the simulation.	
Plotter Block	Display information on model performance.	

TABLE 14. Pilgrim speeds (m/s) at Hajj event for each Group, Fitness and Age [67].

Groups	Level of fatigue	Age groups	
		10-50	50+
SEA, SA, Iran, Africa, Araba, Arabic Gulf and Locals	Rested	1.46	1.2095
	Tired	1.3115	1.0885
	Very tired	1.1658	0.9676
TEAA	Rested	1.3247	1.0995
	Tired	1.1923	0.9896
	Very tired	1.0598	0.8796

TABLE 15. Pilgrims incident rates from Hajj events 2002-2015 [58].

Category	Total pilgrims	Total deaths	Total death %	Male % (number)	Female % (number)	Average age
Iran	1,173,307	738	0.06%	79.81% (589)	20.19% (149)	66.15
TEAA	1,291,338	935	0.07%	27.09% (674)	27.91% (261)	66.90
SEA	2,770,000	4,386	0.15%	62.35% (2,735)	37.65% (1,651)	63.67
SA (Pakistan)	2,127,112	3,579	0.17%	71.46% (2,558)	28.54% (1,021)	59.16
SA (Bangladesh)	1,032,088	1,783	0.17%	83.86% (1,495)	16.14% (288)	58.32
Africa	1,123,000	1,988	0.18%	53.72% (1,068)	46.28% (920)	54.24
SA (India)	1,480,186	2,803	0.19%	71.89% (2,015)	28.11% (788)	64.40
Arab	1,000,500	2,353	0.23%	66.12% (1,556)	33.88% (797)	59.74

TABLE 16. Distances from the main gates to Ka'aba and starting line (The General Presidency for the Affairs of the Two Holy Mosques, Al-Maqsad app, 2019) [59].

Main Gate	Distance from/to main gate to/from Ka'aba	Distance from/to main gate to/from Starting line	Distances from Sayee to main gates
King Abdulaziz	160m	190m	580m
King Fahad	250m	326m	645m
Al-Umrah	164m	269m	453m
Al-Fatah	164m	330m	200m
Al-Marwah (Sayee area)	350m	516m	100m
King Abdullah	360m	504m	340m

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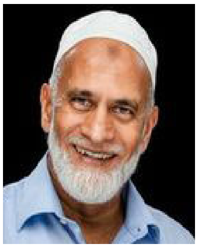

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