
Review of Modelling and Simulating Crowds at Mass Gathering Events: Hajj as a Case Study

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Abstract: The Hajj is an Islamic pilgrimage that involves four main holy sites in Makkah, Saudi Arabia. As the number of participants (pilgrims) attending these events has been increasing over the years, challenges have arisen: overcrowding at the sites resulting in congestion, pilgrims getting lost, stampedes, injuries and even deaths. Although Hajj management authorities have employed up-to-date facilities to manage the events (e.g., state-of-the-art infrastructure and communication technologies, CCTV monitoring, live crowd analysis, time scheduling, and large well-trained police forces and scouts), there is still overcrowding and “unexpected” problems that can occur at the events. These problems can be studied and mitigated by prior simulation, which allows for preparation and deployment of the most appropriate plans for crowd management at Hajj events. This paper presents a comprehensive survey of crowd modelling and simulation studies referring to Hajj.

Keywords: Hajj, Crowd Modelling, Crowd Simulation, Big/Special Events, Mass Gathering

Introduction

- 1.1 Mass gathering (MG) events, such as sport (Olympics games and FIFA world cups), musical concerts, religious events and political events (such as procession, rallies and social riots) frequently occur around the world throughout the year (Krausz & Bauckhage 2011; Alshammari & Mikler 2015; Mahmood et al. 2017). An MG event is defined by World Health Organization (WHO), as “*any occasion, either organized or spontaneous, that attracts a sufficient number of people to strain the planning and response resources of the community, city or nation hosting the event*” (Alshammari & Mikler 2015, p. 574). MG events vary depending on the purpose and the length of the event, number of attendees, location, and whether they are planned or spontaneous. According to Memish et al. (2012), at least 1,000 people must attend the event for it to qualify as an MG. These events present many challenges, such as crowd management, security, and emergency preparedness (Krausz & Bauckhage 2011).
- 1.2 This paper focuses on one of the largest MG events in the world, the Hajj, an annual pilgrimage to the city of Makkah, Saudi Arabia, which consists of a set of religious rituals that should be done within a certain time frame in specific locations (Hajj holy sites) (Seliaman et al. 2001). The Hajj presents enormous challenges for emergency awareness, crowd management and control, and disaster responses to unforeseen natural or human-made threats (Alaska et al. 2017). It is especially difficult for the managing Hajj authorities when all pilgrims complete their rituals at one location and move together, in a short time to the next location (Sowmya & Kumar 2014). Rahman et al. (2017) mention that currently pilgrim numbers exceed 4 million and are expected to increase by 10% every year; many pilgrims are elderly, illiterate and come from developing countries. One of the major issues surrounding this MG event is that Hajj must be completed over a limited and fixed schedule in five days. Hajj rituals are performed as a specific sequence of activities within a geographical area of 400 ha.

The precision and strictness of the rituals result in disasters almost every year, arising from problems such as overcrowding, crowd incidents (lost, injured or dead), medical emergencies, guiding the lost and congestion management (Sowmya & Kumar 2014). In order to face these challenges, Hajj authorities require accurate and real-time estimation of crowds at different locations, to allow intervention before any critical situation occurs (Yaseen et al. 2013). Hajj management also involves monitoring and controlling pilgrims (based on analysis of their movements) and providing early warnings of any unusual behaviours such as a build up at a certain location (Khoziem et al. 2012). Although one of the Hajj crowd management goals is to preserve an adequate level of comfort during pilgrims' movements at Hajj holy sites, a commitment to crowd safety is a key element of crowd management to ensure that participants at Hajj are protected in both emergency situations and normal conditions (Al-Nabulsi 2015). Crowd management also involves developing plans and actions from the examination of causes of previous crowd disasters, to prevent them from occurring again.

- 1.3** This paper summaries previous crowd modelling and simulation studies for Hajj events and their findings through a systematic literature review. Section 1 covers the introduction of the research and the motivation for choosing the Hajj event as a case study (the significance of Hajj as an MG event). Section 2 describes the framework followed in the literature search. Section 3 focuses on describing the event and the holy sites where Hajj is performed. In addition, the significance of Hajj as a mass gathering event, the complexity of Hajj crowd management, the overcrowding challenges and unexpected problems that might occur in future Hajj events are also included. Section 4 reviews the work undertaken on crowd modelling and simulation with special attention on the Hajj. This is followed by a discussion of these studies (Section 5), and finally, conclusions are presented.

Literature Search Framework

- 2.1** A review of the literature was conducted in accordance with PRISMA guidelines to capture relevant studies modelling Hajj events. The following steps were included (Cablová et al. 2017):

A. Aim of review

The main objective of the review is to analyse and summarise results of studies in crowd modelling and simulation for Hajj events under normal and emergency situations, and therefore identify the main crowd management strategies that could be applied.

B. Included research questions

- How could crowd modelling and simulation of mass gathering events be conducted under normal and emergency (evacuation) situations?
- How could crowd modelling and simulation of mass gathering events provide Hajj crowd management guidance and strategies at Hajj holy sites?
- How could crowd modelling and simulation of mass gathering events be improved by combining both micro and macro level modelling techniques?

C. Identifying data sources

Most of the search was undertaken using the databases of IEEE, Science Direct, Elsevier, ACM Digital Library, Springer Link, Research Gate, Oxford database, JASSS, arXiv and The University of Western Australia database (OneSearch). The search was conducted in October-December 2017. This review also used the Saudi Civil Defense website, which is a Saudi Arabian governmental portal for identifying the main future risks at the Hajj holy sites.

D. The process of selection criteria and data collection

The data collection strategy and the selection criteria in this review paper focus on two main topics: Hajj as a case study of MG event and models to simulate crowds at this MG event as a solution for managing these crowds. This review includes both academic and grey literature published in English between 2002 and 2018. Cross-searching was carried out using strings of search terms given in Table 1.

E. PRISMA Flow diagram

Figure 5 (from the Appendix) presents the criteria for inclusion and exclusion of the papers and the PRISMA Flow. Papers were screened and retained if they were: (a) peer-reviewed; (b) accessible in full text form; and (c) specifically presenting a modelling approach, not only presenting the Hajj events. Table 5 (Appendix) presents the final studies selected for this literature review, including their keywords and their compliance with the selection criteria. Duplications were removed, and abstracts and papers were eliminated if they were not eligible (e.g., medical studies focusing primarily on epidemiological aspects).

F. PRISMA Check list: available in Table 6 (Appendix).

Hajj	Crowd modelling and simulation for Hajj events	Modelling and simulation
<ul style="list-style-type: none"> • Hajj as an MG event • Crowd management at Hajj • Hajj management complexity • Crowd behaviours at Hajj • Hajj holy site — The Grand Mosque OR Arafat OR Mina City OR Aljamarat Bridge OR Muzdalifah OR Tawaf OR Sayee • Stoning the devil • Movement from Arafat to Muzdalifah • Hajj challenges • Overcrowding at Hajj event • Crowd incidents during Hajj • Future issues on Hajj crowd management 	<ul style="list-style-type: none"> • Crowd modelling • Crowd simulation • Types for crowd modelling and simulation • Agent-based modelling • Cellular Automata modelling • Social force modelling • Crowd modelling and simulation for Hajj event • Crowd modelling and simulation for normal situations at Hajj event • Crowd modelling and simulation for emergency situation (evacuation) at Hajj 	<ul style="list-style-type: none"> • Significance of modelling and simulation

Table 1: Keywords for the analytic search of the literature. Note: Both US and UK/Australian spelling were considered in the search.

Hajj as a Case Study

- 3.1** Hajj is considered to be the biggest annual mass gathering event in the world (Al-Nabulsi 2015). This pilgrimage is a set of rituals conducted over five days starting from the ninth and ending on of the thirteenth day of the month of Dull Hijjah in the Muslim lunar calendar (Kurdi 2017). Hajj is one of the obligatory five pillars of Islam, and is a duty that the physically able, healthy, and financially able are required to perform once in a lifetime (Memish et al. 2014). A myriad of studies have been conducted on Hajj from different research viewpoints. For example, Kurdi (2017) highlighted that research on Hajj should focus on the safety and quality of pilgrims' experiences. There are several other research studies related to particular Hajj events, for example Tawaf and Sayee rituals, the Aljamarat Bridge ritual, pilgrims' movements between the Hajj ritual places (Arafat, Muzdalifah and Mina city), accommodations at these places, medical issues and Hajj security (Khan 2012). Developing Hajj research projects is critical for several reasons (Kurdi 2017), but many were developed in response to the many injuries and fatalities of pilgrims that have occurred over the last two decades due to uncontrolled crowd movement at the Tawaf and Aljamarat area. As the number of pilgrims has been increasing, existing facilities at Hajj sites get even more congested due to overcrowding.
- 3.2** Alaska et al. (2017) have outlined Hajj is considered as a unique MG event due to both its size, but also to the heterogeneity of the crowd. Each country that might be represented has limited attendance allocations (country quota) and as a result, the majority of pilgrims have to wait for a long time before they leave for Hajj. This process leads to a majority of older pilgrims performing Hajj rituals in extreme environmental conditions (the temperature often exceeds 37 degree Celsius) and moving in large groups at overcrowded locations.

Hajj holy sites

- 3.3** The Hajj rituals are performed at The Grand Mosque (Al-Masjid Al-Haram) and holy sites. These sites include three separate areas (see Figure 1). These are Arafat (approximately 20 km from the Grand Mosque), Muzdalifah (approximately 13 km from the Grand Mosque) and Mina (approximately 6 km from the Grand Mosque). Pilgrims move between Hajj ritual sites by walking, or using dedicated public transport (buses or trains). More than 20,000 buses are used to transport pilgrims between these sites, while trains transport 72,000 pilgrims per hour (Al-Nabulsi 2015).

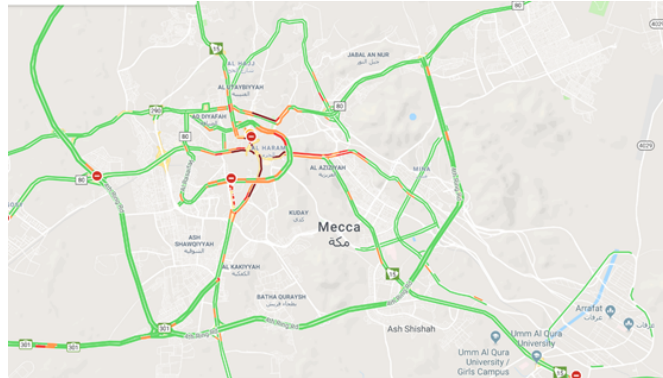


Figure 1: Hajj holy sites, Makkah City (authors' figure using Google Maps).

The Grand Mosque (Almasjid Al-Haram)

- 3.4** The Grand Mosque (Al-Masjid Al-Haram) covers an area of 35.68 ha and includes outdoor and indoor prayer spaces (Rahman et al. 2017). The total capacity of these spaces is about 2 million. When Al-Masjid Al-Haram is completely occupied, it accommodates an average crowd density level of 4 people/m². However, there are specific locations, such as around the Ka'bah, where the crowd density reaches 6-8 people/m².
- 3.5** Al-Masjid Al-Haram has had a number of extensions as a response to the spatial needs of the increasing numbers of pilgrims (Tunasar 2013). Any further expansion has to deal with spatial, architectural, structural, historical, and managerial boundaries. Pedestrian counts and statistics indicate that the number of people inside and outside Al-Masjid Al-Haram (plazas) reaches 366,000 pilgrims at peak time (Shalaby et al. 2013). These people need to exit the space after an hour, as a similar number of people will enter for the next hour.

Mina City

- 3.6** The site of Mina consists of city tents and Aljamarat Bridge. In 1995, the Saudi government built 100,000 tents, to provide temporary accommodation for millions of pilgrims (Al-Nabulsi 2015).

Arafat

- 3.7** The holy site of Arafat is one of the important sites of Hajj. Edrees (2012b) described Arafat as a 1,269 ha area, of which almost half (44% = 558.36 ha) is built up with the remaining (56% = 710.64 ha) representing roads and pedestrian routes. Arafat becomes the most crowded site on the second day of Hajj, because all pilgrims have to arrive, spend half the day and leave after sunset. This poses overcrowding problems at the nine main roads of access to and from Arafat and at Arafat railway stations.
- 3.8** After sunset, all pilgrims leave Arafat for Muzdalifah, which is about 7-8 km to the west. Both of these sites are linked via nine roads for vehicles and two roads for pedestrians. It is estimated that peak pedestrian flow rate between Arafat and Muzdalifah is approximately 500,000 pilgrims per hour (Abdelghany et al. 2012).

Muzdalifah

- 3.9** The site of Muzdalifah is an open area of about 1,000 ha, located halfway between Arafat and Mina (of Research Excellence CORE). After spending the day at the Arafat, pilgrims move to spend their night at Muzdalifah for the

“Al-Nafrah”. This mass movement of more than 2 million pilgrims takes place on buses, trains or by foot. While they are at this holy site, pilgrims collect pebbles for the following days rituals (Seliaman et al. 2001).

Aljamarat Bridge

3.10 Edrees (2012a) describes Aljamarat Bridge as the heart and the bottleneck of Mina city (Figure 2). It has two main pedestrian routes to enter the bridge. The bridge consists of three main pillars, where pilgrims perform the ritual of stoning the devil. These pillars are the most crowded places at the bridge. The peak times at the bridge are on Day 3 (10th of Dul-Hijjah) from dawn till noon, on Day 4 (11th) afternoon and evening and on Day 5 (12th) afternoon. Aljamarat Bridge is additionally considered as a gateway for pilgrims heading to Makkah city to perform Tawaf ritual at the Grand Mosque (Al-Nabulsi 2009).

3.11 After the stampede of 2006, the Kingdom of Saudi Arabia government reconstructed Aljamarat Bridge (as shown in Figure 2) to prevent crowding and recurrent accidents, completing the project in 2010. At peak times, the density of crowd currently reaches 300,000 pilgrims per hour (Alaska et al. 2017). Features of the new bridge are as follows (Imam & Alamoudi 2014):

- 950m long and 80m wide (the previous width was 40m);
- Multi-level (ground, first, second, third and fourth);
- 11 entries and 12 exits;
- 20 hectares surface;
- Integral cooling system (maximum temperature inside the bridge is capped at 29°);
- Many distributed CCTV cameras that transmit live videos to the control room;
- Unidirectional, to prevent counter flows.



Figure 2: Aljamarat Bridge. Source: Edrees (2016).

Hajj rituals

3.12 Several papers have presented features of the individual Hajj events. For example, Zawbaa & Aly (2012) briefly described the Hajj holy sites and their rituals over the five days (8th to the 12th of the Dull Hijjah). Here we summarise them (Table 2) and explain the main challenges at each site.

Hajj Ritual activity	Challenges
Tawaf on the 8 th of Dull Hijjah: The first ritual to perform when pilgrims arrive to Makkah city for Hajj events. They circumambulate the Ka'bah seven times anticlockwise.	The Mataf (Tawaf area) is surrounded by a two-storey building, which accommodates 330,000 pilgrims, and creates overcrowding problem (Abdelghany et al. 2016).
Sayee on the 8 th of Dull Hijjah: This ritual requires walking back and forth between Safa and Marwah hills seven times	The Sayee is a multi-storey area with two-way routes between Al-Safa and Al-Marwah mountains. This area is about 390m long and 33m wide. The crowd density in this area could reach 50,000 people with about 4-8 persons/m ² which creates overcrowding problems (Abdelghany et al. 2016).
Staying in Mina on the 8 th , 10 th , 11 th , 12 th , (sometimes on 13 th): Pilgrims spend most of their days at Mina city	Getting lost is expected at Tents City in Mina, as all these tents are white and look the same.
Standing on the Mount of Arafat on the 9 th of Dull Hijjah: The significant Hajj ritual, where all pilgrims must spend the second day at Arafat.	Many pilgrims spend most of their day time on top of this mountain. Therefore, this mountain is considered one of the most crowded places of Hajj event, creating conditions for many injuries and lost pilgrim cases. Specifically, Edrees (2012b) noted the most crowded places at Arafat are: Al-rahmah Mountain, Alnamirah Mosque, the pedestrian routes between the mountain and the mosque, the Arafat railway stations, and the exit gates from Arafat area.
Staying at Muzdalifah on the 9 th of Dull Hijjah: After the ritual of Arafat, all pilgrims must leave and spend the night in Muzdalifah before the sunrise of the next day.	It is estimated that peak pilgrim flow rate is 500,000 per hour from Arafat to Muzdalifah (Abdelghany et al. 2012). Therefore, crowd incidents (e.g. getting lost) are common during this movement.
Stoning the devil on the 10 th , 11 th , 12 th , (some cases on the 13 th): Throwing stones at the pillars inside the Aljamarat Bridge, except stoning only the biggest pillar on the 10 th day.	Crowd incidents (e.g. getting lost) are expected in this area.

Table 2: Hajj rituals, their dates and challenges

The significance of Hajj event

- 3.13** The study of Owaidah (2015) described Hajj as a unique event for several reasons. First, Hajj represents one of the largest annual events globally, which attracts millions of pilgrims from more than 184 countries (Rahman et al. 2017) within specific areas and for a limited period of time. This exceeds the scale of the mass gathering events for sports events, festivals, or concerts (Krausz & Bauckhage 2011; Turrís et al. 2014). Movements between the locations of Hajj ritual places (Arafat, Mina and Muzdalifah) adds to this unique profile. This is in contrast with most of the MG events (sporting or concerts) which, except for access and egress to the venue, are static (Krausz & Bauckhage 2011).
- 3.14** Second, the Hajj has witnessed many serious crowd incidents. Between 1994 and 2006, there were five major incidents, which led to 1,053 deaths and 1,295 injuries. Also, the Hajj brings together people from diverse cultures, language and countries (e.g. Indonesia, Pakistan, India, Turkey, Iran, Nigeria, Bangladesh, Egypt, European countries, USA, Russia and China). This impacts crowd management for pilgrims, as well as their response

to any potential dangerous hazards. In addition, this cultural diversity dictates how the pilgrims perform the practices, depending on the individual's Islamic doctrine, and this potentially complicates the management of pilgrim movements between the holy places.

- 3.15** A useful classification of the features of MG events was provided by Turris et al. (2014) and presented in Table 7, Appendix. As already highlighted, the multi-site, dynamic nature of the Hajj, combined with its sheer size and socio-demographics, make Hajj an exceptionally intricate case that requires special investigation and specific solutions. Felemban & Basalamah (2011) describe additional characteristics, beyond wide national, social, cultural and educational diversity of participants that make Hajj so distinctive. Foreign pilgrims are 45 years of age or older, and as Hajj is performed once in a lifetime, this can create unexpected emotions and behaviours.

Complexity of crowd management for MG events

- 3.16** Because of their increasing popularity and higher rates/frequencies, safety measures for MG events are central issues on the agenda of MG organizers, to eliminate the likelihood of crowd disasters. Incidents may occur when the crowd densities become extremely high (Krausz & Bauckhage 2011), reaching up to 10 people/m² and the solution is to keep flows separated (both in space and time) (Johansson et al. 2012). At high densities, 'stop-and-go' waves or crowd 'turbulences' may occur and eventually could cause stampedes (Krausz & Bauckhage 2011; Johansson et al. 2012).
- 3.17** In the past decade, the use of scheduling, crowd control, luggage management, video monitoring, and changes in the transport system for the event, have been implemented as solutions for crowd management at various events. In addition, work towards the prevention of crowd disasters included simulations of human behaviour in crowds. Using such simulations, one can identify and defuse situations potentially dangerous in any environment where crowds are present (Johansson et al. 2012).

Crowd Management at Hajj

- 3.18** Khan (2012) identifies Hajj management as the set of decisions to plan, organise and control every activity associated with Hajj events and with the rituals. These decisions are expected to lead to superior crowd performance considering safety, satisfaction and health conditions.
- 3.19** Al-Nabulsi (2015) emphasised that the preparation of Hajj crowd management is a complex task, taking about 12 months to organize for the next Hajj. During this period, extensive planning is prepared by the Hajj governmental agencies for supporting all Hajj sectors to carry out these plans during Hajj and to address major problems that could occur. Managing large crowds, whether pilgrims are performing rituals or moving between Hajj sites, is a daunting task for Hajj organizers (Osman & Shaout 2014; Reda 2016). As Hajj rituals combine two types of crowd dynamics, low-density unmotivated movements and high-density movements (Yaseen et al. 2013), it is essential to understand these processes through the analysis of pedestrian movements in massed locations, depending on varying circumstances (Aljohani 2015). In addition, analysis on overcrowding is critical for preventing people from being trampled or crushed.

Overcrowding at Hajj holy sites

- 3.20** Given the obligatory performance of specific rituals at specific times at specific locations (Reda 2016), large numbers of pilgrims move and gather while performing Hajj rituals, potentially causing bottlenecks. Potential resulting overcrowding can lead to stampedes, traffic and human jams, counter flows, stop-and-go waves, crowd turbulence, and panic (Friberg & Hjelm 2015). All these consequences appear to be unavoidable despite many interventions with positive effects (expansions, careful planning of Hajj events). Thousands of people who have participated in crowded religious events have faced these problems while performing their activities (Yamin 2015). A brief description of each of these potential effects follows.
- 3.21** Stampede is a collective rush of individuals in either unified or random directions (Friberg & Hjelm 2015). Human stampedes are the most common hazard to be seen at mass gathering events. They are characterised by massive flow of individuals in a crowd in response to a perceived danger. Stampedes could result in death due to trampling or suffocation under the high pressure caused by the push in the crowd (Owaidah 2015).
- 3.22** 'Stop-and-go waves' occur when the density of pilgrims is high, and the speed of pilgrims' movement is slow (Friberg & Hjelm 2015). The flow of pilgrims could last more than 20 minutes, and pilgrims start to move in

all directions which can result in pushing and falling (Owaidah 2015). However, when the density of the pilgrim movement becomes larger than stop-and-go waves (crowd density and speed are both high), crowd turbulence is produced (Friberg & Hjelm 2015). A bottleneck is created when the natural flow of the crowd cannot continue due to obstacles (Friberg & Hjelm 2015). The flow of bottlenecks differ depending on the width and length of the flow; longer and narrower flows are slower (Friberg & Hjelm 2015).

- 3.23** Panic “...refer to situations in which individuals have limited information and vision (due to high crowd density and short time of egress), and which result in physical competition and pushing behaviour” (Shiwakoti & Sarvi 2013, p. 12, Owaidah 2015, p. 20). In addition, it could be defined as the breakdown of order when individuals may start anxious reactions in response to a certain event (Helbing & Johansson 2011; Owaidah 2015). In panic situations, many people attempt to escape from the threat, struggling for survival, which could end up crushing individuals in a crowd. Panic effects displayed in crowded locations could include: individuals move faster than normal; there are physical interactions between individuals (e.g. people start to push each other) or disorganized movements; there is build-up of panicked individuals and alternative routes or exits are unnoticed or are used inefficiently (Office 2009; Owaidah 2015). Therefore, overcrowding and bad management at crowded areas lead to panic followed by injuries and crowd disasters (Halabi 2006, p. 28, Owaidah 2015). However, panic could be preventable using effective crowd management as a part of emergency planning (Drury et al. 2013; Owaidah 2015).
- 3.24** There are additional issues which increase the overcrowding problems at Tawaf area inside the Grand Mosque (Shuaibu et al. 2015): a) pilgrims who finished their Tawaf ritual are always close to Ka’aba. After they complete their ritual, they proceed in a pattern that forces them to collide with other pilgrims; b) congestion and blockage are due to the queuing at the Ka’ba gate and the ‘Black Stone’; c) the entrance to the Tawaf area is not restricted to certain gates and pilgrims easily flow into the area through different directions, although physical constraints are the main challenges. Finally, traffic and human congestion can result in blocking the Hajj main roads for hours. Providing extra lanes to existing road infrastructure can ease congestion problems (Yamin 2015).
- 3.25** In conclusion, overcrowding and panic at religious sites can be contained, and crowd incidents could be prevented by efficient crowd management including sufficient prior planning, infrastructure improvements, deployment of more security officers and information technology improvements (H & S. 2015). Moreover, understanding the role of the pilgrims themselves, such as their movements and behaviours, should be included in the crowd management process for training and education (H & S. 2015).

Previous Hajj crowd incidents and their main causes

- 3.26** Numerous crowd incidents have occurred in the past two decades at Hajj events. These incidents varied by location (at Haram area and Hajj ritual sites, specifically Mina city) and causes, and are presented below.

Incidents at the Grand Mosque

- 3.27** Evidence from Table 8 (Appendix) shows that many of these crowd incidents were caused by human fault, with a range of different consequences. A tragic crane incident in 2015 led to 107 deaths and 200 injuries. However, minor incidents at Haram, such as getting lost (in large numbers in 2006, 2011 and 2013), occur recurrently. Due to the crowdedness of Haram area, incidents may occur in the future, which could lead to stampedes, congestion and exhaustion (Edrees 2016).

Incidents at Aljamarat Bridge, Mina

- 3.28** Table 9 (Appendix) shows most of the crowd incidents were at Aljamarat Bridge, Mina City, during the ritual of ‘stoning the devil’. Edrees (2012a) identified the Aljamarat Bridge as the bottleneck of Mina. In the past, the Bridge had two main pedestrian routes for entry, from Muzdalifah and Almuasim. A stampede at the bridge in 2006 led to 1,035 deaths and 721 injuries (Helbing et al. 2007). The Office (2009) described the reasons for the 2006 disaster as overcrowding, enormous crowd pressures, lack of crowd management at the bridge and pushing forwards too quickly to perform the stoning ritual. Some pilgrims also insist on performing the stoning ritual on the right of the pillars, which could cause crowding around these pillars. The new infrastructure has alleviated this risk, and these incidents decreased radically since.
- 3.29** A stampede caused crowd incidents at Tents City in 2015. This incident was at the crossing of streets 204 and 223 (Khan & Noji 2016). These numbers show the ‘unpredictability’ of crowd incidents in Hajj, their impact, and that it is critical to prepare for these unexpected events (Aljohani 2015). All of these could be achieved by simulation.

Incidents at Arafat and Muzdalifah

- 3.30** Table 10 (Appendix) shows no casualties at Arafat or Muzdalifah. However, cases of lost people have occurred at these places. For example, in 2011, a total of 30,000 pilgrims were lost at Haram and Hajj holy sites (Amro & Nijem 2012). Edrees (2012b) explained some reasons for incidents in these areas: pilgrims insisting on approaching, climbing and standing on Alrahmah Mountain; pilgrims insisting on praying at Alnamirah Mosque at Arafat; exits from Alnamirah mosque and Arafat streets being joined which caused aggregation of pilgrims; pilgrims laying down on Arafat streets and paths; some pilgrims waiting at exit paths early to leave Arafat and head to Muzdalifah; traffic jams occurring at Muzdalifah after pilgrims leave Arafat; and lack of guidance and information distributed to pilgrims.

Observations on past incidents

- 3.31** The Defence (2017) has drawn attention to a number of past incidents and indicated future issues which may present at Hajj holy sites. Past observations include: construction incidents; walking/crossing traffic (not using pedestrian pathways); walking through emergency pathways; resting at the pedestrian pathways; lack of awareness about Hajj sites emergency exits (evacuation precautions); problematic crowd behaviours inside pedestrian tunnels; and falling rocks while climbing Al-Rahmah Mountain (Arafat).
- 3.32** Jbira & Lakhoua (2012) offered insight into why future stampedes, congestion and crowd panic at Aljamarat Bridge might occur. For example, new pilgrims may find it difficult to recognise the ground floor entrance due to the crowds. There is also a general lack of understanding of instructions provided, and there are not enough tools or methods to alert event organisers to the problem before complications occur. Therefore, crowd modelling by simulating crowd scenarios under different situations could help in planning better crowd management and control strategies (Sharma et al. 2018).

Literature Survey Results

Crowd modelling and simulation types

- 4.1** Bakar et al. (2017, p. 1) identified modelling as “...a method of solving problems, in which the approach under investigation is controlled by a basic pro-test that illustrates the genuine framework and/or its operation”. They identified simulation as “...a decision support tool to predict the system behaviour by answering the ‘what-if scenarios’”. In addition, crowd simulation is the process of replicating the movement of large numbers of entities, characters, agents or pedestrians. It represents the motion and behaviours of the crowd either via two-dimensional (2D) or three-dimensional (3D) computer graphics (Nasir & Sunar 2016).
- 4.2** Crowd simulation models can be used to predict crowd behaviours and movements and performance issues related to infrastructure (buildings and public facilities) designs (Sarmady et al. 2010). These models could also be used to estimate evacuation time in emergency situations.
- 4.3** Many modelling and simulation methods for pedestrian crowds have been proposed. They can be categorised into two broad categories: (a) Microscopic models, dealing with individual pedestrians, or (b) Macroscopic models, dealing with aggregate characteristics of the crowds (Rahman et al. 2017). They are presented in the following subsections.

Agent-Based Models (ABM)

- 4.4** ABMs are microscopic models focusing on the interaction among heterogeneous agents, each with their own set of characteristics/endowments and following their rules of interaction, according to their objectives (Bonabeau 2002). Given that agents are autonomous, responsive, proactive and social, the macro-level outcomes cannot be directly predicted, but they rather emerge from the interactions.

Social Force Models (SFM)

- 4.5 SFMs are widely used to model human pedestrians (Bakar et al. 2017). These models are suitable to imitate human behaviours and can generate collective behaviour of pedestrian flow, as individuals follow others. These models can produce smooth movements, accurate and realistic results (Sarmady et al. 2010).

Cellular Automata (CA) models

- 4.6 CA uses 'cells' occupied by agents (Bakar et al. 2017). These models examine the movement of agents from one cell to another empty cell. Sarmady et al. (2010) describe CA models as using simple and flexible transition rules to identify the cell to which an agent will move next. CA models for crowd applications divide the movement space into big grid cells, each cell accommodating an agent. During simulation, agents stay in the current cell or move into one of the neighbouring cells. One of the limitations of the CA setup is the similar speed of the agents in the cells and the identical size of the cells. In real life, pedestrians have different movement speeds and the space they occupy during rituals also differs.
- 4.7 Regarding crowd modelling and simulation for Hajj events, Hajj crowd management and evacuation procedures during both normal and emergency situations justify significant attention, given their recurrent nature (Mohamad et al. 2014). Modelling and simulation are therefore important, as they are tools that can be used to assess safety and take appropriate precautions. Reda (2016) concluded that in order to manage crowd movements efficiently at Hajj events, crowd behaviours, dynamics, formation causes, and formation patterns should be better understood. Crowd modelling and simulation offer opportunities for studying and analysing crowd behaviours and crowd dynamics, in order to predict crowd movements. In addition, Alaska et al. (2017) mentioned that using crowd simulation models helps to assess the best methods of grouping and scheduling pilgrims, managing and controlling crowds and luggage management, as well as informing pilgrims of changes in the transport system used during the event.

Significance of crowd modelling and simulation

- 4.8 Computer modelling and simulation can be used to inform and optimise decision-making for implementing change in real-life scenarios (Tayan 2010). In regard to crowd events, computational techniques are needed for observing behaviour in dense crowds, such as trampling, falling, collision, or pushing (Kurdi et al. 2015). This is particularly relevant for optimising the movements and flow of pilgrims between the holy ritual places at the Hajj events. Simulation models are 'dynamic' and allow unpredictable behaviours to appear: "Goal of the simulation is to reproduce realistic scenarios of such situations evolving in real-time involving a large number of virtual human agents" (Ulicny & Thalmann 2001, p. 163, Office 2009, p. 193). Crowd simulation of different scenarios could help in achieving better crowd management and control strategies (Sharma et al. 2018).
- 4.9 Kabalan (2016) highlighted several reasons for using crowd dynamics simulation: help to devise measures aimed at increasing the level of comfort of pedestrians; suggest detail planning for pedestrian paths; and manage crowds to ensure a safe environment for a large number of pilgrims. Crowd evacuation in emergencies (in a short time and under stress conditions) could be improved. In addition, simulation could help to understand the principles and mechanisms of collective motion and self-organisation phenomena such as shock waves, oscillation at bottlenecks and lane formation.

Previous Hajj simulation studies

- 4.10 Computer simulation is a fitting tool to investigate crowd movements and evacuation processes (Kabalan 2016). Due to several overcrowding incidents at Hajj, efforts have been made to address these processes by using crowd simulation models (Johansson et al. 2012). Sharma et al. (2018) showed that data collection (such as video records and traffic counts) enables validation of crowd simulation of Hajj events, offering suggestions for changes in event management and control, and event execution and infrastructure. This literature review focuses on two groups of Hajj studies that simulate rituals at two main locations; Tawaf in the Grand Mosque, and Jamarat at Aljamarat Bridge.

Simulating crowds during Tawaf and Sayee rituals

- 4.11** Crowd simulation for Tawaf and Sayee rituals uses complex flows of motions, variable velocities, high density and heterogeneous (varieties) populations (Kurdi et al. 2015). In addition, there are significant factors that most of the previous studies focused on, such as the Tawaf (circumambulating the Ka'bah) area, pilgrim behaviours and the crowd size (Kurdi et al. 2015). Regardless of the modelling approach, many earlier studies had a common limitation which can now be overcome: the inability to capture the scale of real events. Most models used ABM, SFM and CA approaches.
- 4.12** Mulyana & Gunawan (2010) simulated pilgrims performing Tawaf as 'intelligent' agents, able to recognise the environment and to undertake various actions. Agents' behaviours were depicted to reflect pilgrims' behaviours in real situations. Each agent needs to know the individual current location to determine appropriate behaviour and do specific activities according to the environment. For example, during Tawaf ritual, each agent circles the Ka'bah in an anticlockwise direction, to avoid collisions at crowded places in the Tawaf area, such as gathering around the Black Stone (Al-Hajar Al-Aswad), Maqam Ibrahim and Hijr Ismail. The objective of Mulyana and Gunawan's (2010) work was to develop Hajj crowd simulation based on agents able to recognise the environment and perform natural and complex behaviours. The results of this type of simulation were superior, demonstrating more realistic behaviour for Tawaf ritual (Kurdi 2017). This simulation can be used for training pilgrims before they perform the ritual. However, the limitation of this study is that the number of agents to be simulated was low; also, some optimisation in this model can be applied, such as using better collision detection in the crowded places.
- 4.13** Khan & McLeod (2012) developed an ABM to investigate the effect of Al-Masjid Al-Haram courtyard layout on pilgrims' movements during Tawaf, to analyse pilgrims' crowd properties (features) and provide a tool for the Hajj authorities to manage crowds, maximise the safety of pilgrims (lack of collisions) and protect their health (against spread of disease). They developed the TawafSIM micro-level simulator, which models pilgrims performing the Tawaf ritual, to explore the impact of crowd characteristics and management preferences on Tawaf performance with respect to pilgrims' satisfaction, health and safety. The authors simulated 42 scenarios in 12 different categories, using colours to indicate the congestion at the Mataf area (Figure 3, colours denote their spiralling status). Red dots indicate that pilgrims are spiralling inward from the edge of the crowd boundary to the external half of the circles. Green dots represent maintaining the radius at circles near the Ka'bah whereas blue dots are for pilgrims who are spiralling outwards. Black dots are for pilgrims who have completed the seven rounds and are spiralling outwards to exit from the crowds. The 5th category, yellow, which is dispersed throughout the crowd, represents agents who change their route in order to avoid crowd collisions.

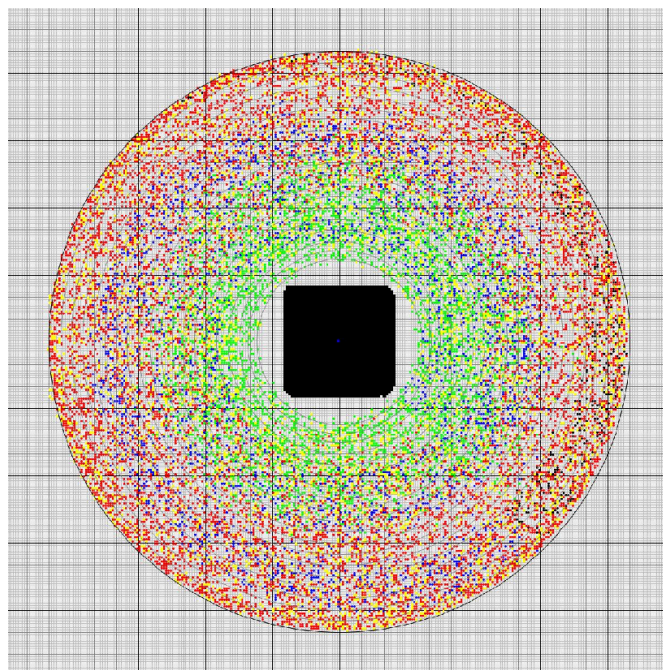


Figure 3: Snapshot of TawafSim simulator. Source: Khan & McLeod (2012).

- 4.14** Khan & McLeod (2012) combined ABM with Finite State Machine (FSM), which uses a geometric collision avoid-

ance algorithm. The FSM algorithm was used to model each pilgrim (agent) and to control agent's activities when interacting with other agents. Kurdi (2017) mentioned that although this study provides many recommendations regarding crowd management, crowd behaviour and facility layout for safety and throughput, it could be enhanced by using an appropriate crowd simulator with the ability to simulate large numbers of pilgrims and to develop behaviour metrics. This study could be also applied for the crowd management of Tawaf ritual on the other two levels, and the Sayee area of Al-Masjid Al-Haram.

- 4.15** Kim et al. (2015) modelled the physical interactions between agents by using an interactive velocity-based multi-agent framework relying on the agents' ability to anticipate and avoid collisions. This framework was able to model complex behaviour relating to social and cultural rules. The authors used FSM to define a series of behaviours and parameters for their physical interaction model. The work simulated 35,000 agents in dense scenarios (8 agents/m²). As a result, this work was able to simulate complex interaction between agents and dynamic obstacles in the environment, generating many emergent behaviours. Che et al. (2015) mentioned that this study combined velocity-based and avoidance algorithms with FDM to model both physical forces and interactions between the agents and obstacles. Additionally, it allowed agents to anticipate and avoid collisions during local navigations: e.g. pilgrims performing Tawaf at Mataf area while avoiding each other and avoiding colliding with Hijr Ismail or Maqam Ibrahim. However, they modelled a small number of agents, compared to the number of pilgrims during Hajj.
- 4.16** Sarmady et al. (2008) proposed a CA model to simulate pilgrims performing Tawaf rituals. They pointed out that most of the previous systems were unable to simulate pilgrims' movements in Tawaf area with enough agents. Therefore, their proposed model was developed to simulate large crowds of pilgrims and combined a macroscopic model for the crowd movement with CA to simulate collision avoidance and to identify the shortest paths. Their integrated system was capable of simulating between 20,000 to 23,000 agents in real time. In addition, they compared the velocity of the crowds obtained from empirical observations and simulation snapshots with photos taken from the Tawaf area to validate their model. This study was mainly focused on simulating a large number of pilgrims moving at the Mata area (Mohamad et al. 2014) however, their system failed to consider behaviour such as pushing, falling and grouping (Mohamad et al. 2014).
- 4.17** Siddiqui & Gwynne (2012) used a crowd simulation model known as EXODUS to simulate pilgrims performing the Sayee ritual at the Grand Mosque (Almasjid Alharam). Their model was used to understand individual behaviour when simulating large crowds in emergency situations. This study focused on analysing both pedestrian and evacuee behaviour and used observations by the lead author during his own pilgrimage in 2008 (notes, video footages and still photographs) to calibrate the model. These observations recorded the pilgrims' actions along with the surrounding influential factors and the resulting emergent conditions. The authors decided to use EXODUS due to its ability to produce a range of outputs that allow performance to be examined at the individual, group or population level. Three scenarios were examined: Scenario 1 used the model's default movement parameters with travel speed ranges between 1.2 – 1.5 m/s; Scenario 2 used modified movement parameters to reflect the observed travel speed around 1.0 m/s; and Scenario 3 was similar to scenario 2, but included a subset of the procedural activities, to reflect the individual actions. Two sets of simulations were conducted for each scenario. In the first set (Case A), an individual pilgrim was simulated performing Sayee 3.5 times. In the second set (Case B), a representative population of 15,000 pilgrims was simulated. The individual routes were affected by the introduction of individual task itineraries and producing more complex and vibrated behaviours (Case A), while in Case B, the more complex routes were combined to produce emergent behaviours similar to those observed in the real events. Therefore, this model showed the relationship between pilgrims (agents) and the levels of congested areas from different observations from the Tawaf ritual (Shuaibu et al. 2015). This model was used for prior planning of crowded events, examining all possible and anticipated scenarios for managing crowds in normal and dangerous situations. This process could also be conducted for any crowded places outside Al-Masjid Al-Haram.
- 4.18** Zainuddin et al. (2009) simulated the circumambulation of Ka'bah using the crowd simulation model SimWalk. The authors underlined two main problems in the Tawaf area. First was the large number of pilgrims in this area, which causes pilgrims to push each other. Second, the area has unlimited bi-directional entries, which result in pilgrims entering and exiting at the same time and causing congestion. Therefore, this study suggested various mitigation measures to ease the pilgrim flows in the Tawaf area: building a spiral path, encircling the Ka'ba venue seven times, but with the path entrance at the outermost fold, and the completion of the Tawaf at the innermost fold, leading to an underground tunnel; and waiting points around the Ka'ba, which can direct pilgrims to walk around the Ka'ba without building congestion. The results of this study showed that building the spiral path is an effective solution in ensuring smooth crowd flows in the Tawaf area. However, the authors mentioned that this approach might not be realistic to implement, as the underground tunnel involves additional costs and may be infeasible (historical items located below the Tawaf area). As a result, an alterna-

tive approach was building an overhead bridge that links the centre of the Tawaf area to the exit of the Grand Mosque. The main drawback of this study is simulating only 1,000 pilgrims, which is insignificant compared to the real number of pilgrims (300,000) in Tawaf ritual during Hajj.

- 4.19** Dridi (2014) used PedFlow to simulate pilgrims performing rituals in the Tawaf and Sayee areas. The model was verified and validated using data collected during Hajj 2009 and included walking time and the number of pilgrims and crowd density at the Grand Mosque gates before and after each prayer. The following methods were applied: 1) Comparisons of PedFlow results with video recordings of Hajj 2009; 2) Comparisons between PedFlow results and other simulation models results, such as Simulex/Myriad. The Pedflow results were more sophisticated in predicting the high density of crowd and crowd dynamics; 3) Sensitivity analysis showing the effect of different input values on the simulation outputs. Dridi (2014) concluded that PedFlow can produce realistic crowd motion with agents moving at different speeds and under different situations using avoidance action (collisions). However, this model should be tested again with new updated data of crowds at Mataf area and Sayee area at Al-Masjid Al-Haram or other locations.
- 4.20** Nasir & Sunar (2016) presented a study to simulate group behaviour while performing Tawaf under normal circumstances. Their study implemented SFM, modified to simulate group dynamics, by integrating the flocking technique into the SFM. Flocking is a popular technique to simulate large groups of agents. Reynolds (1987), the proponent of this technique, was inspired by the behaviour seen in flock of birds and schools of fish. He introduced an approach of simulating groups behaviours based on the interaction between agents following simple rules, called 'BOIDS'. In the Tawaf simulation, this integrated model was used to simulate group behaviours while in the circular motion. Several behaviours were observed through the simulation. For example, the group members maintained their position to be as close as possible to each other. In addition, if one of the group members was left slightly behind, the whole group would reduce its speed accordingly, and the separated pilgrim increase his/her speed to catch up with the group. This study is useful to understand pilgrims' behaviours in a crowd in both normal and emergency situations and to aid Hajj authorities to plan for optimal crowd flow and prevent crowd incidents. However, the applicability of this model to large scale crowd is yet to be determined, as the number of the simulated agents was only 500.
- 4.21** Mahmood et al. (2017) proposed an ABM crowd simulation and analysis framework. They developed the model in a software platform called "Anylogic" and integrated it with external modules for optimisation and analysis of the crowd simulation results. Anylogic crowd simulation model provides both user-friendly integrated environment and an efficient simulation engine. These tools allow modellers to quickly create and simulate dense crowds. The main features of the proposed framework were: the ability to model a large crowd in a spatial environment at real-scale (e.g. stadium, malls, large mosques and spatial networks); simulating movement of high density crowds and their complex behaviours such as emergency evacuation using different experimental settings; and detailed assessment of crowd management and control strategies to evaluate evacuation plans.
- 4.22** This framework was used to evaluate three emergency evacuation strategies during Hajj: Random Crowd Evacuation (the crowd selects its exit randomly); Shortest Regional Distance (the crowd select the nearest gate by using the shortest path for evacuation); Genetic Algorithm (the crowd select the best evacuation solution that will minimise the total evacuation time for the whole crowd).
- 4.23** Using the proposed model for simulating crowd evacuation from the Grand Mosque led to the following results were obtained from 10 runs/strategy (Table 3).

Simulation factors	All three evacuation strategies
Population	10,000 agents
Evacuation time	1.3 minute
Average speed of the crowd	Min = 1.0 m/s; Max = 2.0 m/s Most likely = 1.4 m/s

Table 3: Anylogic results. Source: Mahmood et al. (2017)

- 4.24** More needs to be done to observe the crowd density at peak times of all Hajj days, in all sections of Al-Masjid Al-Haram and compare to the capacity. This process will help Hajj organisers to identify the crowded zones at observed locations, to direct and distribute pilgrims to uncrowded spaces to perform their Tawaf ritual and thus decrease congestion at the main Mataf area.
- 4.25** The results were similar for the three different crowd evacuation strategies. The authors stated that when the crowd simulation would include more complex physical behaviour, the performance of those evacuation strategies may differ. They also suggested that the proposed framework can be easily implemented as public safety

and security management for events, being beneficial for developing and supporting decisions. However, several drawbacks limit its application: no crowd management strategies are devised for normal situations; and the number of tested agents in the simulation is small compared to the real number of pilgrims located inside and outside the Grand Mosque at Hajj peak time (over 300,000 pilgrims).

Simulating crowds at Aljamarat Bridge ('Stoning the Devil' ritual)

4.26 Based on a video analysis of unique recordings of the human stampede of 2006, Helbing et al. (2007) presented explanations for the causes of the tragical incident, as well as solutions for improving the crowd management. According to their analysis, two sudden transitions led to "stop-and-go" flows at the entrance of the old Aljamarat Bridge and then "turbulent flows" and pressures occurred when the crowd density reached 9 pilgrims/m². The resulting stampede led for the loss of 346 lives and many injured pilgrims. Helbing et al. (2007) recommended several improvements:

- Increasing the stoning capacity and the crowd capacity at different levels of the bridge, by extending the three pillars using elliptical shape, as previously suggested by Dr Keith Still;
- Preventing crowd accumulation in the plaza around the Aljamarat Bridge and further designing a new plaza that allows the General Security to easily balance the pilgrims flows between the ground floor and the Northern and Southern ramps of the first floor; this would preclude overcrowding and breakdown of pilgrim flows;
- Replacing the two-way pilgrim flows on the streets and on the bridge by a one-way traffic, to avoid obstructions and counter-flows;
- Using a systematic scheduling system to homogeneously distribute pilgrims at the bridge;
- Providing an automated counting system of pilgrims and constant monitoring using the CCTV cameras.

4.27 Some of these recommendations were later appreciated to have had a key role in improving the organisation of the ritual after 2006: e.g., the separation of the flow's directions and the reservation of space for emergency operations at Aljamarat Bridge (Al-Kodmany 2013).

4.28 Al-Kodmany (2013) used both Myriad 2 and Legion crowd models to test the new design of the Aljamarat Bridge. Legion is an ABM platform, focusing on modelling and simulating crowd behaviour, and ingress (entrance) and egress (exits) scenarios. In simulating evacuation scenarios, three situations were presented: choosing a random exit, choosing the nearest exit and all agents choosing the same exit. Agents can make movement decisions based on their current situations and constraints. A similar ABM platform, Myriad 2, was used for multiple purposes and at various scales. Its uniqueness relies on the integration of three different analytic techniques: network analysis; spatial analysis; and agent-based analysis. For instance, Myriad 2 can model a transport network for a large scale crowds, then simulate the crowd movements and behaviours within a complex environment, such as a railway station, and then experiments with many types of crowd reactions. The uniqueness of this model is in the integration of: *Network analysis* (to simulate crowd movements in large complex spaces); *Spatial analysis* model (analyse the utilised spaces in complex environments); and *Agent analysis* (for modelling systems with complex behaviours and experimenting with many types of options of crowd reactions).

4.29 Al-Kodmany (2013) applied specific parameters in the Myriad 2 simulations, such as entrance and exit width, building crowds around the pillars and crowd flows at the bridge. On the other hand, Legion was used to test the safety impacts. Results of combining Legion and Myriad 2 for Aljamarat Bridge indicated that the new bridge design, the capacity and the elliptical shapes of the new pillars would improve pilgrims' safety at the bridge. As an extension, Dridi (2014) joined Simulex with Myriad 2 to measure queue progression when approaching Aljamarat Bridge. Simulex is a micro simulation model for emergency egress combined with Myriad 2 to extract the information on pilgrim's crowd density, speed and arrival time at the bridge (AlGadhi & Still 2003). A Legion model was developed to improve the conceptual design of the Jamarat Bridge (Dridi 2014). Data on Aljamarat bridge capacity, viewing range of the three Jamarat pillars, in-flux and out-flux of the crowd, speed and resting times, ingress (entrance) capacity and increase in the exit capacity were used for validation. Moreover, the approved design of the new Jamarat Bridge, with five levels was further tested in other simulation models (Illyas 2013).

4.30 Illyas (2013) applied NetLogo, a widely known platform for ABM, to simulate activities at the Aljamarat Bridge. This platform allows users, both beginners and experienced, to design, programme, test and analyse scenarios, and develop a scientific understanding (Railsback et al. 2017). NetLogo is popular due to its professional design

and packages, good visualization, comprehensive documentation, and high-level programming language with many built-in commands and data types specialised for ABMs. Furthermore, it has an integrated graphical user interface for performing simulation experiments (Kornhauser et al. 2009). For Aljamarat simulation, this model presented two types of agents: aggressive agents, who walk faster and move directly towards the Jamarat pillars without considering other pilgrims; and considerate agents, who walk slower and avoid crowds when moving towards the Jamarat. The simulation results match the real capacity of bridge (125,000 pilgrims per hour per level), and the rate of pilgrim flow on the bridge of 35 pilgrims/sec. A number of parameters were defined for this model. For example, the time required to perform this ritual, the stone throwing and the viewing range of the three Jamarat pillars. In addition, the analysis of pilgrims queuing and standing beside the Jamarat pillars was conducted for different shapes (circle and elliptical shapes). However, this study has not included many behaviours exhibited while performing the Ramy Jamarat ritual. These might include congestion effects (e.g. stampede), emotion or anxiety that may lead to irrational behaviours, or avoiding collisions and physical interaction. Nevertheless, this study could improve managing crowds at Aljamarat Bridge by examining each Jamarat level divided into zones, to identify the crowded areas at each level. This will help Hajj authorities to identify critical crowded zones on all Aljamarat Bridge levels, and to distribute pilgrims to other less crowded levels before any harm could happen.

- 4.31** Fayoumi et al. (2011) used STEPS, a crowd management microsimulation tool, to simulate pilgrim dynamics under normal and in emergency situations. The model was used to optimize crowd movement and assist in emergency egress management. In addition, their system was used to predict individuals' movements in 3D-space. The authors ran four crowd simulation scenarios (models) A, B, C and D to improve the performance of pilgrim stoning processes in Hajj. Another main simulation result of this study was that the number of pilgrims performing Ramy ritual can be increased by 25% by increasing the Jamarat basin by 20%. The results of this study could be used to develop the simulation of pilgrims on the Jamarat Bridge, expanding the architectural design of the Bridge and Jamarat pillars and assessing whether these expansions would affect the crowd management positively or negatively.
- 4.32** Klüpfel (2007) used a dynamic crowd model called PedGo, to simulate evacuation scenarios of large crowds of pilgrims (reaching 100,000 pilgrims at Aljamarat Bridge). This simulation showed how crowds separate during the process of evacuation, using the eight exits displayed in Figure 4.
- 4.33** Al-Kodmany (2013) highlighted that PedGo can run in real time. The outputs of this model include visual analysis, evacuation time, density plots and walking time. PedGo was used to test scenarios of crowd evacuation from Aljamarat Bridge. It simulated 100,000 pilgrims being evacuated from the bridge to the exits after 10 minutes of the emergency. Al-Kodmany (2013) mentioned that Klüpfel (2007) focused on the "potential" aspect of this simulation, as he assumed the pedestrians have a common sense of the task and all of them are aware of all the nearest exits from their locations and taking the shortest path. This study could also be used to simulate huge numbers of pilgrims in other places, such as Al-Masjid Al-Haram.



Figure 4: Simulating 100,000 agents to evacuate from Aljamarat Bridge. Sources: Klüpfel (2007).

- 4.34** PedGo is a crowd simulation model developed by Meyer-König and Klüpfel (Sarmady et al. 2007) to simulate emergency evacuation of larger crowds. It was an outcome of a research project called BYPASS (Al-Kodmany 2013). PedGo can use different properties for the simulated pedestrians (e.g. maximum speed, patience, dawdle and sway) applying the normal probability distribution. In addition, as PedGo is a Cellular Automata (CA) model, it simulates the microscopic level of local movements of the pedestrians. Moreover, PedGo was applied to simulate emergency evacuation from crowded places (e.g. the egress from a sports stadium) (Klüpfel & Meyer-König 2005). In their review, Kuligowski et al. (2005) compared PedGo model with other crowd models. They mentioned that the purpose of the model is to model and simulate crowd movement, and the evacuation of pedestrians from crowded places, such as buildings, ships, and other kinds of public transportation. PedGo uses as a network structure that divides the geometry of its floor plan into 0.4×0.4 m grid cells and represents the space that is filled up by a person. In PedGo model, a set of rules is applied to all pedestrians regarding their movement in the model. However, PedGo is claimed to be a Multi-Agent model, but the description of the

model does not correspond with the definition of autonomous agents (Kukla 2007) and the agents do not communicate with each other. This model is a stochastic model, which means that the behaviour of the modelled agent is determined by a parameterised probability distribution; each cell has a rule and transition occurs (e.g. if the next cell is empty, the agent can move into it) (Kukla 2007). PedGo is a microscopic CA model (Kukla 2007).

4.35 In conclusion, most of the simulation studies on Hajj have adopted and implemented ABM, CA and SFM, when modelling the Tawaf and Aljamarat rituals. ABM allows for heterogeneous agents to interact using simple rules and examining the emerging behaviour, while CA models can simplify crowd movements and representation, by using direct mapping of agent behaviours and cell update rules. However, CA (cells) do not present realistic behaviours and individual features. SFM provide continuous position representation of agents and use crowd movement foundation representing crowds as one homogeneous group (Sun 2013). These models can simulate normal crowd behaviours and evacuation situations, and some of them can simulate both conditions. Crowd modelling and simulation play a significant role in the development of new crowd management practices at mass gathering events.

Discussions

5.1 This paper presented a survey of crowd and pedestrian models used to test and examine crowd behaviours and movements for Hajj events. Previous studies on modelling and simulating pilgrims in Haram Mosque and Aljamarat Bridge have provided many insights on how to improve crowd management and have highlighted the limitations of both modelling and practices. Many studies used ABM and focused on studying pilgrims' behaviours at these sites, how pilgrims interact with each other (collision avoidance) and with the surroundings of these sites. Other studies used CA to model each individual movement while performing Tawaf and Sayee at Haram, and how pilgrims progress and choose empty spaces in their movement. Finally, other studies used SFM to analyse pilgrim flows, while they perform Tawaf ritual around the Ka'bah. Very few scholars (e.g. Sarmady et al. 2008) applied a combination of microscopic and macroscopic models, to study both pilgrim interactions with each other and their movements as a crowd at Tawaf ritual. Most of these Hajj studies focused on using types of Microscopic models (ABM, CA and SFM), which indicates that each pilgrim's behaviour and action can eventually affect the crowd movement at Haram and Aljamarat Bridge. Table 4 identifies the main gaps from the literature review:

- All studies used micro models, except Sarmady et al. (2008) used a combination of micro and macro;
- All studies only covered a simulation of two holy sites, presenting a fragmented view of the Hajj event;
- Most maximum number of agents simulated did not exceed 25,000, which is a small number compared to the real number of pilgrims at Hajj events.

Table 4: Analysis of previous studies.

Authors	Study Description	Model Type	Advantages/Benefits	Crowd Management Strategies	Man- Gap
Al-Kodmany (2013)	Myriad 2 specifically developed by Professor Still for this purpose. The software provided detailed information on Aljamarat Bridge, such as arrival capacity, throwing area, space (as crowd density was four pilgrims/m ²) passing areas and egress capacity.	ABM	Detailed information about individuals Natural matching between agents and individuals	Provided assistance for the Hajj authorities for the development of pilgrims queuing and entering the Aljamarat Bridge.	These techniques could be used to improve Hajj crowd management and architectural designs at other Hajj places (e.g. Al-Masjid Al-Haram).

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Authors	Study Description	Model I Type	Advantages/Benefits	Crowd Management Strategies	Man- Gap
Dridi (2014)	Applies the crowd simulation model PedFlow ; verification and validation with video recordings of Hajj event 2009. Comparisons between PedFlow and Simulex/Myriad simulation models results.	ABM	Pedflow is more sophisticated in predicting the density of crowd and its dynamics. It can produce realistic crowd motion with agent moving at different speeds and under different situations while using collisions avoidance actions.		Using this simulator with updated data from crowds of pilgrims performing Tawaf and Sayee rituals. Using this simulator for other Hajj crowd places (e.g. Aljamarat Bridge, Arafat and Muzdalifah).
Fayoumi et al. (2011)	STEPS , a microsimulation tool, was used for simulating pilgrim dynamics under normal and emergency situations. This tool was additionally used to predict individual' movements in 3D space.	CA	Detailed information about individuals' actions and behaviours. Natural matching between agents and individuals		This technique could be used to study the relationships between expanding other Hajj places and the crowd behaviours, movements and flows.
Illyas (2013)	NetLogo ABM model used for the ritual of 'stoning the devil' at the Aljamarat Bridge. Used to simulate the effect of different parameters of pilgrim movements, such as space between pilgrims and Jamarat pillars, hitting range, etc.	ABM	Able to simulate two types of individual behaviours. Able to simulate different shapes of Aljamarat pillars.	Analysing pilgrims queuing while standing beside the three Aljamarat pillars for the throwing ritual.	This model could simulate agents at other places, such as Tawaf area.
Khan & McLeod (2012)	Investigated the effect of Al-Masjid Al-Haram courtyard layout, pilgrim crowd properties and crowd management on crowd safety a spread of diseases via ABM.	ABM	Provides guidance on crowd management for Tawaf area.	Provided main guidelines for Tawaf crowd management (42 crowd simulation scenarios).	The crowd management results could be applied on other Hajj ritual sites.

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Authors	Study Description	Model I Type	Advantages/Benefits	Crowd Management Strategies	Man- Gap
Kim et al. (2015)	Method to model complex physical interaction between agents by using an interactive velocity-based multi-agent FSM framework. 35,000 agents were simulated in dense scenarios (8 agents/m ²), while interacting with other agents and with obstacles.	ABM	Combining velocity-based and collection avoidance algorithms with physical forces to model interactions between agents and obstacles in the simulated environment. It allows agents to anticipate and avoid collisions during local navigations (walking in the environment).	—	Improving modelling by simulating pilgrim behaviour (e.g. interacting with other agents, with the environments' obstacles and avoiding collisions).
Klүpfel (2007)	PedGo applied to simulate evacuation scenarios of large crowds (100,000 pilgrims at Aljamarat Bridge). This simulation showed how crowds were separated in the evacuation process.	CA/multi-agent	Natural matching between agents and individuals.	Analysing emergency situation (evacuation) of more than 100,000 pilgrims on Aljamarat Bridge.	This tool could be used to simulate evacuation scenarios at other Hajj places.
Mahmood et al. (2017)	Integrating Anylogic model with external modules for optimization and analysis of the crowd simulation, to evaluate crowd evacuation strategies.	ABM	Model large crowds in a spatial environment at real-scale, simulation emergency evacuation under different experimental settings. Complex behaviour, such as emergency evacuation, using different experimental settings. Detailed assessment of crowd management and control strategies.	This framework can be implemented for public safety and security management during events and other supporting decisions.	The study did not present any crowd management strategies in normal situations. The number of the simulated agents is small compared to the real number of pilgrims located inside and outside the Grand Mosque at Hajj peak time.
Mulyana & Gu-nawan (2010)	Simulated pilgrims performing Tawaf as "intelligent" agents. Simulation matched the practical performance of real pilgrims during Tawaf and Sayee rituals.	ABM	The simulation could be used for training purposes before travelling to Al-Masjid Al-Haram (Kurdi et al. 2015).	Used as a pilgrims training tool for performing Hajj rituals.	Increasing the number of informed agents, to match the real number of pilgrims, could be tested. Using simulation not only for training, but also for improving Hajj crowd management.

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Authors	Study Description	Model I Type	Advantages/Benefits	Crowd Management Strategies	Gap
Nasir & Sunar (2016)	SFM and flocking techniques applied for simulation of group behaviour in a crowd in normal situation while performing the Tawaf ritual	SFM	Present several behaviours that were observed from the simulation of Tawaf.	This model helps to understand pilgrim behaviour in a crowd and assists Hajj authorities to plan for optimal crowd flows and prevent incidents.	Simulate group behaviours under emergency situations such as evacuation. Increase the number of agents to the real number of pilgrims at Hajj. The flocking technique could be used for validating simulating ABM simulation of individual behaviour in a group.
Sarmady et al. (2008)	Combined macroscopic model for crowd movements and CA, for collision avoidance and use of shorter paths during Tawaf rituals. The integrated system was capable of simulating up to 23,000 agents in real time.	Hybrid model (Macro + CA)	The ability to simulate a large number of crowds on a single computer [42]	—	Focus additionally on simulating crowd behaviours while performing Tawaf ritual (e.g. interacting with other agents, with obstacles and avoiding collisions).
Siddiqui & Gwynne (2012)	Used EXODUS model for simulating pilgrims performing the Sayee ritual at the Grand Mosque (Almasjid Alharam).	CA	This model was used to understand the importance of individual behaviour when simulating large crowds of pilgrims (15,000 agents).	Provided prior planning for emergency situations for Hajj events.	This tool could be used to simulate evacuation scenarios at other Hajj places (e.g. Al-Masjid Al-Haram).
Zainuddin et al. (2009)	Simulated the circumambulation of Ka'ba using SimWalk. This study suggested various mitigation measures to ease the pilgrims' flows in the Tawaf area. The results of this study showed that building the spiral path is an effective solution in ensuring a smooth flow in Tawaf area.	SFM	The ability to design and analyse crowd flows using SFM (Kurdi et al. 2015)	Proposed to design new exits for pilgrims after completing their Tawaf rituals (e.g., building an underground tunnel or overhead bridge to exit from the Grand Mosque without interfering with the arriving pilgrims).	Increase the number of simulated pilgrims to match the real number of pilgrims.

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Conclusion

6.1 Mass gathering (MG) events pose significant planning and management challenges. As a case study, Hajj is an

MG event which attracts millions of pilgrims to perform rituals at four holy sites. This paper reviewed the latest crowd modelling and simulation studies, and the most important models and software packages used for the Hajj in both normal and emergency situations. Hajj is relevant as an MG event primarily because of its scale and one that faces major problems, such as overcrowding, congestion, people getting lost, stampedes, injuries and deaths. Therefore, Hajj authorities are interested in using models and latest technologies for planning the events and for managing pilgrims at the holy sites. Crowding problems can be studied prior to the events using simulation models. This paper identified three main groups of modelling techniques — agent-based modelling, cellular automata and social force — each with specific benefits and limitations. The paper critically assessed these models, identifying potential applications to other rituals or locations and directions for new research, which can assist the planning and operation of MG event, irrespective of their nature.

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Appendix: PRISMA 2009 Flow Diagram

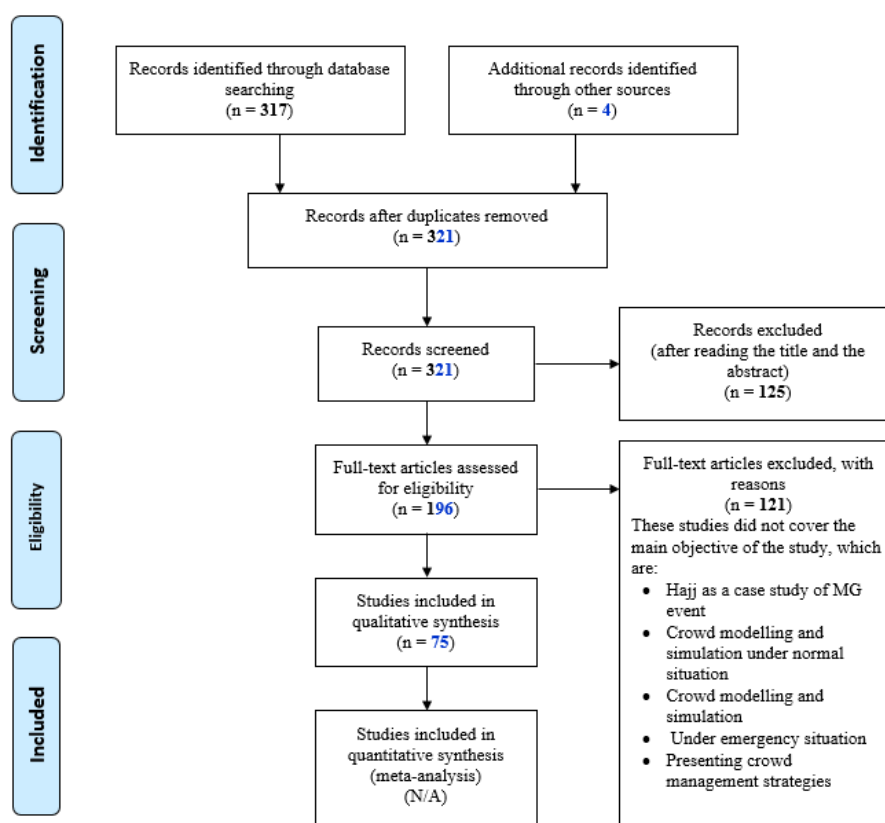


Figure 5: PRISMA flow diagram for the literature review.

Table 5: Selection criteria for the literature review

Study and year of publication	Publication Keywords	Selection Criteria				
		Using Hajj as a case study of MG event	Describing some detail information of Hajj event	Crowd modelling and simulation for normal situation	Crowd modelling and simulation under emergency situation	Presenting crowd management procedures and strategies
Alaska et al. (2017)	Mass gathering, Jamarat, Hajj.	✓	✓			
Abdelghany et al. (2016)	Hajj, crowd dynamics, pedestrian flow.	✓	✓			
Abdelghany et al. (2012)	Pedestrian movements, crowd management, Makkah.	✓	✓			
AlGadhi & Still (2003)	Hajj, Aljamarat Bridge, crowd modelling, crowd simulation.	✓	✓	✓		
Aljohani (2015)	Hajj, crowd dynamics, Holy Mosque, Holy sites.	✓	✓			
Al-Kodmany (2013)	Crowd management, software tools, design testing, operational plans and Hajj	✓	✓	✓	✓	✓
Al-Kodmany (2011)	Hajj, Aljamarat Bridge, stoning the devil, crowd safety.	✓	✓			
Al-Nabulsi (2015)	Hajj, crowd, psychology.	✓	✓			
Al-Nabulsi (2009)	Hajj, mass gatherings, risk assessment.	✓	✓			
Alqahtani et al. (2017)	Hajj, mass gathering, stampede, crowd disaster, crowd incidents, Hajj incidents	✓	✓			
Alshammari & Mikler (2015)	Mass gatherings, Hajj.	✓	✓			
Amro & Nijem (2012)	Hajj, pilgrims, tracking, lost.	✓	✓			

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Study and year of publication	Publication Keywords	Selection Criteria				
		Using Hajj as a case study of MG event	Describing some detail information of Hajj event	Crowd modelling and simulation for normal situation	Crowd modelling and simulation under emergency situation	Presenting crowd management procedures and strategies
Bakar et al. (2017)	Crowd modelling, crowd simulation, crowd evacuation, modelling and simulation			✓	✓	
Bonabeau (2002)	Modelling, ABM.			✓		
Che et al. (2015)	Crowd modelling, crowd simulation.			✓		
Curtis et al. (2011)	Hajj, Tawaf, crowd modelling	✓	✓	✓		
Dridi (2014)	Pedestrian simulation, verification of simulation tools	✓	✓	✓		✓
Edrees (2016)	Hajj, urban design, crowd control, Aljamarat Bridge, open space.	✓	✓			
Edrees (2012b)	Hajj, pilgrims, Arafat, crowded sites, urban, congested sites.	✓	✓			
Edrees (2012a)	Hajj, control pilgrims, density, movement, Aljamarat Bridge.	✓	✓			
Fayoumi et al. (2011)	Crowd management simulation tools, stoning in Hajj and Aljamarat Bridge	✓	✓	✓	✓	
Felemban & Basalamah (2011)	Hajj, pilgrims, localization, city of Makkah.	✓	✓			
Friberg & Hjelm (2015)	Crowd behavior, human behavior, crowd dynamics, crowd incidents, Mina.	✓				
of Research Excellence (CORE)	Hajj, Holy sites, Makkah.	✓	✓			

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Study and year of publication	Publication Keywords	Selection Criteria				
		Using Hajj as a case study of MG event	Describing some detail information of Hajj event	Crowd modelling and simulation for normal situation	Crowd modelling and simulation under emergency situation	Presenting crowd management procedures and strategies
Helbing et al. (2007)	Hajj, Aljamarat Bridge, crowd management	✓	✓			✓
Illyas (2013)	Crowd simulation, Hajj, Ramy, stoning the devil, Jamarat and NetLogo	✓	✓	✓	✓	✓
Imam & Alamoudi (2014)	Hajj sites, pilgrimage, Mina, tent city.	✓	✓			
Jbira & Lakhoua (2012)	Hajj, Mina, congestions.	✓	✓			
Johansson et al. (2012)	Hajj, mass gathering, crowd modeling, crowd simulation	✓	✓	✓		
Kabalan (2016)	Crowd modelling, crowd simulation, crowd dynamics.			✓		
Khan & Noji (2016)	Hajj, mass gathering, stampede, Mina, crowd management.	✓	✓			
Khan (2012)	Hajj, crowd management, crowd modelling, crowd simulation, ABM, Tawaf.	✓	✓	✓		
Khan & McLeod (2012)	Crowd simulation, agent-based modelling and simulation, mass gathering, Hajj, Tawaf, decision support systems, operations management	✓	✓	✓	✓	✓

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Study and year of publication	Publication Keywords	Selection Criteria				
		Using Hajj as a case study of MG event	Describing some detail information of Hajj event	Crowd modelling and simulation for normal situation	Crowd modelling and simulation under emergency situation	Presenting crowd management procedures and strategies
Khozium et al. (2012)	Hajj, crowd management, crowd density, crowd monitoring, Nafrah.	✓	✓			
Kim et al. (2015)	Hajj, Tawaf simulation, Multi-agent simulation, Physical interactions	✓	✓	✓		✓
Klüpfel (2007)	Hajj, Al-Jamaramt Bridge, crowd modelling, crowd simulation, pedestrian flow, route choice	✓	✓	✓	✓	✓
Klüpfel & Meyer-König (2005)	Crowd modelling and simulation, PedGo				✓	
Kornhauser et al. (2009)	Modelling, NetLogo.			✓		
Krausz & Bauckhage (2011)	Mass Gathering events, crowd management					✓
Kukla (2007)	Crowd modelling and simulations			✓	✓	
Kuligowski et al. (2005)	Crowd modelling and simulation			✓	✓	
Kurdi (2017)	Crowd modelling, crowd simulation, crowd behaviors, Hajj, Sayee.	✓	✓	✓	✓	
Kurdi et al. (2015)	Hajj, modelling, simulation, ABM, crowd modelling, crowd simulation, Tawaf, Sayee.	✓	✓	✓	✓	

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Study and year of publication	Publication Keywords	Selection Criteria				
		Using Hajj as a case study of MG event	Describing some detail information of Hajj event	Crowd modelling and simulation for normal situation	Crowd modelling and simulation under emergency situation	Presenting crowd management procedures and strategies
Mahmood et al. (2017)	Emergency evacuation strategies, agent-based crowd simulation, Hajj scenarios.	✓	✓	✓	✓	✓
Memish et al. (2012)	Mass gatherings, Hajj.	✓	✓			
Memish et al. (2014)	Hajj, religious festival, gathering	✓	✓			
Mohamad et al. (2014)	Hajj, crowd modelling, crowd simulation, Tawaf.	✓	✓	✓	✓	
Mulyana & Gunawan (2010)	crowd simulation, hajj, agent, behavior, pilgrim	✓	✓	✓		✓
Nasir & Sunar (2016)	Computer animation, modelling and simulation techniques and crowd simulation	✓	✓	✓	✓	✓
Osman & Shaout (2014)	Hajj, crowd management, pilgrims.	✓	✓			
Owaidah (2015)	Hajj, crowd management, crowd incidents.	✓	✓			
Paeveen & Aldhlan (2016)	Hajj, missing pilgrims, pilgrims tracking, lost pilgrims.	✓	✓			
Rahman et al. (2017)	Mass gathering, Hajj.	✓	✓			
Railsback et al. (2017)	Modelling, NetLogo.			✓		
Reda (2016)	Hajj, Hajj management, pilgrims, crowd dynamics.	✓	✓			

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Study and year of publication	Publication Keywords	Selection Criteria				
		Using Hajj as a case study of MG event	Describing some detail information of Hajj event	Crowd modelling and simulation for normal situation	Crowd modelling and simulation under emergency situation	Presenting crowd management procedures and strategies
Sarmady et al. (2010)	Crowd modelling, crowd simulation, crowd movement, CA models.			✓		
Sarmady et al. (2008)	Behavior modelling, crowd modelling, simulation, Cellular Automata, multi-agent and pedestrian	✓	✓	✓		✓
Sarmady et al. (2007)	Hajj, Tawaf ritual, crowd modelling and simulation	✓	✓	✓	✓	✓
Defence (2017)	NA (website)	✓	✓			
Seliaman et al. (2001)	Hajj, Holy sites, Arafat, Muzdalifah.	✓	✓			
Sharma et al. (2018)	Hajj, crowd management, crowd modelling, crowd simulation	✓	✓	✓		
Shalaby et al. (2013)	Holy city, Makkah, urban area, large-scale event, religious event.	✓	✓			
Shuaibu et al. (2015)	Hajj, Tawaf, crowd movement, pedestrian, congestion.	✓	✓			
Siddiqui & Gwynne (2012)	Pedestrian dynamics, simulation, analysis, crowd and Hajj	✓	✓	✓	✓	✓
Sowmya & Kumar (2014)	Mass gathering, Hajj.	✓	✓			

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Study and year of publication	Publication Keywords	Selection Criteria				
		Using Hajj as a case study of MG event	Describing some detail information of Hajj event	Crowd modelling and simulation for normal situation	Crowd modelling and simulation under emergency situation	Presenting crowd management procedures and strategies
Sun (2013)	Crowd modelling, crowd simulation, crowd behavior, individual behavior.			✓		
H & S. (2015)	Crowd management, Hajj	✓	✓			
Tayan (2010)	Hajj, Holy sites.	✓	✓			
Tunasar (2013)	Hajj, pilgrims, Mecca.	✓	✓			
Turris et al. (2014)	Mass Gathering events	✓				
Office (2009)	Crowd behavior, Hajj, crowd modelling, crowd simulation.	✓	✓	✓	✓	✓
Yamin (2015)	Hajj, crowd management, crowd, pilgrims.	✓	✓			
Yaseen et al. (2013)	Hajj, pilgrimage, Mecca, crowd safety.	✓	✓			
Zainuddin et al. (2009)	Hajj, crowd modelling, crowd simulation, Tawaf simulation, pedestrian flow, Ka'aba, SFM.	✓	✓	✓		✓
Zawbaa & Aly (2012)	Hajj, Umrah, Hajj rituals.	✓	✓			

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Table 6: PRISMA Checklist

Section/topic	#	Checklist item	Reported on page #
TITLE			
Title	1	Identify the report as a systematic review, meta-analysis, or both.	Title of the paper
ABSTRACT			
Structured summary	2.1	Provide a structured summary including, as applicable: background; objectives; data sources; study eligibility criteria, participants, and interventions; study appraisal and synthesis methods; results; limitations; conclusions and implications of key findings; systematic review registration number.	2.1
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of what is already known.	2.1
Objectives	4	Provide an explicit statement of questions being addressed with reference to participants, interventions, comparisons, outcomes, and study design (PICOS).	2.1
METHODS			
Protocol and registration	5	Indicate if a review protocol exists, if and where it can be accessed (e.g., Web address), and, if available, provide registration information including registration number.	N/A
Eligibility criteria	6	Specify study characteristics (e.g., PICOS, length of follow-up) and report characteristics (e.g., years considered, language, publication status) used as criteria for eligibility, giving rationale.	Table 5: <i>Selection criteria for the literature review</i>
Information sources	7	Describe all information sources (e.g., databases with dates of coverage, contact with study authors to identify additional studies) in the search and date last searched.	2.1
Search	8	Present full electronic search strategy for at least one database, including any limits used, such that it could be repeated.	2.1
Study selection	9	State the process for selecting studies (i.e., screening, eligibility, included in systematic review, and, if applicable, included in the meta-analysis).	2.1
Data collection process	10	Describe method of data extraction from reports (e.g., piloted forms, independently, in duplicate) and any processes for obtaining and confirming data from investigators.	N/A
Data items	11	List and define all variables for which data were sought (e.g., PICOS, funding sources) and any assumptions and simplifications made.	N/A
Risk of bias in individual studies	12	Describe methods used for assessing risk of bias of individual studies (including specification of whether this was done at the study or outcome level), and how this information is to be used in any data synthesis.	N/A
Summary measures	13	State the principal summary measures (e.g., risk ratio, difference in means).	N/A
Synthesis of results	14	Describe the methods of handling data and combining results of studies, if done, including measures of consistency (e.g., I ²) for each meta-analysis.	Table 5: <i>Selection criteria for the literature review</i>
Risk of bias across studies	15	Specify any assessment of risk of bias that may affect the cumulative evidence (e.g., publication bias, selective reporting within studies).	N/A

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Section/topic	# Check-list item	Reported on page #	
Additional analyses	16	Describe methods of additional analyses (e.g., sensitivity or subgroup analyses, meta-regression), if done, indicating which were pre-specified.	N/A
RESULTS			
Study selection	17	Give numbers of studies screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally with a flow diagram.	Figure 5: <i>PRISMA flow diagram for the literature review</i>
Study characteristics	18	For each study, present characteristics for which data were extracted (e.g., study size, PICOS, follow-up period) and provide the citations.	2.1
Risk of bias within studies	19	Present data on risk of bias of each study and, if available, any outcome level assessment (see item 12).	N/A
Results of individual studies	20	For all outcomes considered (benefits or harms), present, for each study: (a) simple summary data for each intervention group (b) effect estimates and confidence intervals, ideally with a forest plot.	N/A
Synthesis of results	21	Present results of each meta-analysis done, including confidence intervals and measures of consistency.	N/A
Risk of bias across studies	22	Present results of any assessment of risk of bias across studies (see Item 15).	N/A
Additional analysis	23	Give results of additional analyses, if done (e.g., sensitivity or subgroup analyses, meta-regression [see Item 16]).	N/A
Study characteristics	18	For each study, present characteristics for which data were extracted (e.g., study size, PICOS, follow-up period) and provide the citations.	2.1
DISCUSSION			
Summary of evidence	24	Summarize the main findings including the strength of evidence for each main outcome; consider their relevance to key groups (e.g., healthcare providers, users, and policy makers).	5.4 to 6.1
Limitations	25	Discuss limitations at study and outcome level (e.g., risk of bias), and at review-level (e.g., incomplete retrieval of identified research, reporting bias).	5.4 to 6.1
Conclusions	26	Provide a general interpretation of the results in the context of other evidence, and implications for future research.	6.1
FUNDING			
Funding	27	Describe sources of funding for the systematic review and other support (e.g., supply of data); role of funders for the systematic review.	6.1

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Event dimension	Category/Criterion	Examples
Demographics	Event Type	Races, sport events (e.g., cycling), religious pilgrimages, cultural events, and music festivals
	Geography	Environment bounded or unbounded, shifting or fixed footprint, site (and egress, multi or single venue)
	Temporality	Duration (days, hours), time of year, time of day, season, recurrent annual event vs first-time event, peak time of attendance
Dynamics	Crowd Type	Gender mix, age mix, families, disabilities, special populations
	Crowd behavior	Density, activity levels, queuing, movement, behaviour
Design	Protective Factors	Predispositions, motivations, crowd movement, and flow
	Special Hazards	Crowd resilience, health promotion, illness prevention, police/security onsite
	Onsite Health Services	Climate, weather conditions, road/rail traffic, obstacle course, infectious disease exposure, alcohol and drug use, mosh pits, fireworks
		First aid only, higher level of care

Table 7: Classification of MG events

Holy site/ Incident type	Past incidents at The Grand Mosque (Al-Masjid Al-Haram)	Causes of deaths
Major (death)	September 2015, 107 deaths at Haram (Alqahtani et al. 2017)	Collapse of a crane
Middle (injury)	September 2015, 200 injuries at Haram, from the collapse of Crane (Alqahtani et al. 2017)	
Minor (lost)	<ul style="list-style-type: none"> • 2006 – 2,500 lost at Haram (Paeveen & Aldhlan 2016) • 2011 – 3,000 lost at Haram and Hajj holy sites (Amro & Nijem 2012; Paeveen & Aldhlan 2016) • 2013 – 7,998 lost cases (Paeveen & Aldhlan 2016) 	

Table 8: Past incidents at the Grand Mosque (Al-Masjid Al-Haram)

Table 9: Past incidents at Mina city

Holy site/ Incident type	Past incidents at Mina City and Aljamarat Bridge	Causes of deaths
Major (death)	September 2015, 769 deaths (Khan & Noji 2016; Alqahtani et al. 2017)	Unknown reasons caused a stampede at crossing of street 204 and 223 at tents city, Mina (Khan & Noji 2016; Alqahtani et al. 2017)
	January 2006, 346 deaths (Khan & Noji 2016; Alqahtani et al. 2017)	Some pilgrims were stumbled over and caused stampede for arriving pilgrims at the eastern access ramp (Khan & Noji 2016; Alqahtani et al. 2017)
	February 2004, 251 deaths (Alaska et al. 2017; Khan & Noji 2016; Alqahtani et al. 2017)	Unorganised pilgrims at the bridge carrying their luggage and belongings. They caused stampede for the crowd's movements on the bridge (Alaska et al. 2017; Khan & Noji 2016; Alqahtani et al. 2017)

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Holy site/ Incident type	Past incidents at Mina City and Aljamarat Bridge	Causes of deaths
	February 2003, 14 deaths (Aljohani 2015; Alaska et al. 2017; Alqahtani et al. 2017)	Unknown reasons caused a stamped at Aljamarat Bridge during the ritual of stoning the devil (Aljohani 2015; Alaska et al. 2017; Alqahtani et al. 2017)
	March 2001, 35 deaths (Imam & Alamoudi 2014; Alaska et al. 2017; Alqahtani et al. 2017)	Unknown reasons caused trampling at Aljamarat Bridge during stoning the devil (Imam & Alamoudi 2014; Alaska et al. 2017; Alqahtani et al. 2017)
	April 1998, 119 deaths (Aljohani 2015; Alaska et al. 2017; Alqahtani et al. 2017)	Panic, which caused trampling and falling pilgrims during the stoning ritual (Aljohani 2015; Alaska et al. 2017; Alqahtani et al. 2017)
	April 1997, 343 deaths (Khan & Noji 2016; Alqahtani et al. 2017)	Cooking gas canisters explosions that caused fire at tents city in Mina (Khan & Noji 2016; Alqahtani et al. 2017)
	April 1994, 270 deaths (Imam & Alamoudi 2014; Alaska et al. 2017; Aljohani 2015; Khan & Noji 2016; Alqahtani et al. 2017)	Crowd waves which crushed the crowds on the bridge (Imam & Alamoudi 2014; Alaska et al. 2017; Aljohani 2015; Khan & Noji 2016; Alqahtani et al. 2017)
	July 1990, 1426 deaths (Imam & Alamoudi 2014; Aljohani 2015; Khan & Noji 2016; Alqahtani et al. 2017)	Stampede inside Alma'aisim tunnel to Haram, due to failed ventilation (Imam & Alamoudi 2014; Aljohani 2015; Khan & Noji 2016; Alqahtani et al. 2017)
Middle (injury)	September 2015, 1278 injuries at crossing of street 204 and 223 at tents city, Mina (Alqahtani et al. 2017)	
	January 2006, 289 injuries from a stampede at Aljamarat Bridge during the ritual of 'stoning the devil' (Alqahtani et al. 2017)	
	February 2004, 244 injuries, from a stampede at Aljamarat Bridge during the ritual of 'stoning the devil' (Alqahtani et al. 2017)	
	April 1998, 188 injuries, from trampling at Aljamarat Bridge (Alqahtani et al. 2017)	
	April 1997, 1500 injuries, fire at tents city in Mina (Imam & Alamoudi 2014; Khan & Noji 2016; Alqahtani et al. 2017)	
Minor (lost)	2011, 30,000 lost cases at Haram and Hajj holy sites (Amro & Nijem 2012; Paeveen & Aldhlan 2016)	

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Holy site/ Incident type	Arafat Past	Muzdalifah Past
Minor (lost)	2011, 30,000 lost at Haram and Hajj holy sites (Amro & Nijem 2012; Paeveen & Aldhlan 2016)	2011, 30,000 lost at Haram and Hajj holy sites (Amro & Nijem 2012; Paeveen & Aldhlan 2016)

Table 10: Past incidents at Arafat and Muzdalifah

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