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Analyzing the Impact of Social Distancing on the Stoning Ritual of the Islamic Pilgrimage

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Received February 28, 2022; revised May 22, 2022; accepted May 29, 2022; published June 30, 2022

Abstract

The COVID-19 pandemic has resulted in a profound impact on large-scale gatherings throughout the world. Social distancing has become one of the most common measures to restrict the spread of the novel Coronavirus. Islamic pilgrimage attracts millions of pilgrims to Saudi Arabia annually. One of the mandatory rituals of pilgrimage is the symbolic stoning of the devil. Every pilgrim is required to perform this ritual within a specified time on three days of pilgrimage. This ritual is prone to congestion due to strict spatiotemporal requirements. We propose a pedestrian simulation model for implementing social distancing in the stoning ritual. An agent-based simulation is designed to analyze the impact of inter-queue and intra-queue spacing between adjacent pilgrims on the throughput and congestion during the stoning ritual. After analyzing several combinations of intra-queue and inter-queue spacings, we conclude that 25 queues with 1.5 meters of intra-queue spacing result in an optimal combination of throughput and congestion. The Ministry of Hajj in Saudi Arabia may benefit from these findings to manage and plan pilgrimage more effectively.

Keywords: Pedestrian simulation, Social Distancing, Hajj, Pilgrimage, Islamic Pilgrimage, Ramy, Stoning the devil, Jamarat

This work was supported by the Deanship of Scientific Research, Vice Presidency for Graduate Studies and Scientific Research, King Faisal University, Saudi Arabia [Project No. GRANT65]

http://doi.org/10.3837/tiis.2022.06.010 **ISSN : 1976-7277**

1. Introduction

Pilgrimage in Islam, also called Hajj, is a religious obligation for every Muslim who can afford it financially and physically [1]. It is performed annually in the holy city of Makkah in Saudi Arabia. The obligatory rituals of pilgrimage span five days of the last month of the Islamic calendar. The vast population of Muslims in the world, comfortable traveling, improved infrastructure in Makkah, and better management and hosting services provided by Saudi Arabia have resulted in a continuous increase in the number of pilgrims in the last few decades. The total number of pilgrims peaked at 3.16 million in 2014 [2]. Saudi Arabia restricted the number of pilgrims to about 2.5 million between 2014-2019 because of the expansion project at the Grand Mosque of Makkah (also known as Masjid al-Haram), one of the main sites for pilgrimage. The outbreak of novel coronavirus (SARS-CoV-2) in 2020 [3] resulted in a curtailed pilgrimage with only 1,000 pilgrims [4].

One of the mandatory pilgrimage rituals is the symbolic stoning of the devil (also called Ramy al-jamarat) [5]. In this ritual, pilgrims pelt stones at three pillars in the city of Mina near Mecca. All pilgrims must perform this ritual on three consecutive days of pilgrimage. On the third day of pilgrimage, every pilgrim throws seven stones at the largest pillar only, while on the next two days, each pilgrim hurls seven pebbles at each of the three pillars. The ritual has strict time restrictions and the time required to complete the ritual in a day is about 5.5 hours, although recently, the Saudi religious scholars have ruled that pilgrims can perform the ritual from sunrise to sunset. Pilgrims perform this ritual in a confined area. Also, pilgrims need to get close to the pillars to be able to hit them. These factors have resulted in stampedes in the area claiming many lives and causing injuries to others [6]. **Fig. 1** summarizes significant incidents in pilgrimage since 1975, with the number of pilgrims injured or died during these incidents [6]–[9].

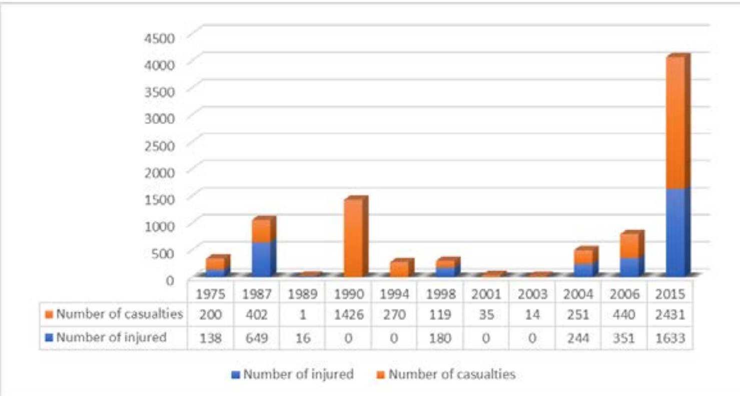

Fig. 1. Summary of incidents in pilgrimage since 1975

Most of the incidents mentioned above occurred on Jamarat bridge. The old single-tier Jamarat bridge was replaced by a 5-level bridge in 2007 for improved security of pilgrims. The length of the structure is 950 meters, while the width varies from 60 to 97 meters. The main objective of the new design is to avoid stampedes and congestion as much as possible. Some of the design choices based on these measures are as follows [10]:

- Elliptical pillars replaced the circular pillars to increase the throughput of the structure.
- The structure is entirely free from internal columns.
- The entire area permits the unidirectional flow of pedestrians only. Pilgrims enter the

bridge from one side and exit from the other side without crossing pedestrians approaching from any other direction.
- Several enhancements to the escalators including increased landing area, increased ingress area, safety stairs, and safety barriers.
- The new design has improved pilgrims' lines of sight to prevent queueing and anxiety.
- Egress ramps on the bridge provide the desired throughput of 125,000 pilgrims/hour.

The simulation studies have estimated the maximum throughput of the structure to be 300,000 pilgrims/hour.

COVID-19 pandemic has affected every walk of life [11]. After lockdowns of varying degrees in almost all parts of the world [12], [13], we have started accepting to live with the novel coronavirus by adopting several precautionary measures such as wearing face masks, social distancing, and maintaining a high level of hygiene [14]–[16]. Although the approval process of several vaccines has been fast-tracked for emergency use [17]–[19], and they are available in most parts of the world [20], preventive measures are still necessary [21]. Hence, in the coming years, pilgrimage may be held with strict COVID-19 safety measures. This study focuses on the social distancing of pilgrims during the ritual of the stoning of the devil. As mentioned above, the strict spatiotemporal requirement of this ritual makes it a bottleneck in planning the pilgrimage. Social distancing will severely impact the throughput of the Jamarat Bridge, where pilgrims perform this ritual. This study proposed a simulation model to study the effect of social distancing on throughput and congestion during the stoning ritual. We have analyzed the impact of various inter-queue and intra-queue spacing settings on throughput and congestion during the ritual of stoning the devil.

The rest of the paper is organized as follows. Related works are presented in section 2. The proposed model is detailed in section 3. Experimental results are given in section 4, and the Discussion section concludes the paper.

2. Related Work

Strict time and space constraints on pilgrimage rituals, millions of pilgrims performing these rituals, and the diversity of people pose severe challenges to the management of pilgrimage and the safety of pilgrims. The researchers have presented various proposals to facilitate pilgrims in three aspects. The first aspect regards proposing architectural changes for pilgrimage rituals to increase throughput and improve the safety of pilgrims. Second, researchers have proposed various educational tools to create awareness among pilgrims. The last aspect refers to effective management of pilgrimage to minimize risks for pilgrims and maximize infrastructural efficiency.

The work on education and awareness includes an agent-based simulation of various pilgrimage rituals by Mulyana and Gunawan [22] and a 3D model of Makkah by Schneider et al. [23]. Koshak developed a GIS (Geographic Information Systems) simulation to move groups of pilgrims to and from the Mina area [24]. They created a base map of the site and layers for various area features to simulate the schedule developed by the Saudi Ministry of Hajj to assist pilgrims' smooth movement. Another related study was performed by Andijani et al. to simulate shuttle buses between Muzdalifah and Arafat areas [25]. Most recently, researchers have proposed using augmented and virtual reality-based solutions for training pilgrims before arriving in Makkah to prepare them for pilgrimage rituals [26]–[28].

Although management of the pilgrimage is a daunting task because of the large scale of the event, two mandatory rituals, in particular, have a higher potential for causing pilgrim congestion. Tawaf is the first of these rituals that refers to pilgrims circumambulating the

Kaaba building seven times in a counterclockwise direction. The maximum radius of the courtyard in which this ritual is performed (called Mataf) is about 48 meters [29]. Also, all pilgrims must perform this ritual within a limited period. These factors make the circumambulation ritual highly prone to congestion. The second ritual is the symbolic stoning of the devil. In the following, a brief overview of works related to the ritual of circumambulation is followed by a thorough literature review of the stoning ritual. Al-Haboubi & Selim propose to develop a spiraling path around the Kaaba with one ramp for entrance into the yard and a single exit point to ensure a smooth and uninterrupted movement of pilgrims [30]. This proposal requires significant changes to the existing infrastructure. We require a thorough study to find out the benefits and drawbacks of the proposal before implementation.

Several works have used agent-based modeling to study the behavior of pilgrims during circumambulation rituals [31], [32]. Koshak & Fouda used Global Positioning System and Geographic Information Systems to study the movement of pilgrims in circumambulation [33]. Löhner et al. proposed comparing social force and agent-based models for simulating circumambulation [34]. Kolivand et al. proposed an enhanced basic social force model with four new parameters and used it to simulate the circumambulation ritual [35]. The consideration of additional crowd characteristics such as grouping, gender, intention outlook, and walking speed makes it a generalized model. Mohamed & Parvez propose using automatically activated barriers to manage queues of pilgrims willing to kiss the black stone [36]. Although kissing the black stone is not a mandatory ritual, the proposal may significantly reduce congestion in the Mataf area as this ritual is a significant source of congestion in the area. Some other salient works related to circumambulation include [37]–[39].

Till 2006, Jamaraat bridge had only one tier for performing the ritual of stoning the devil. Several studies suggested improvements for the safety of pilgrims [40]–[42]. Since the construction of the multi-level bridge in 2007, several researchers have analyzed various aspects of the new structure.

Fayoumi et al. conclude that a 20% increase in the length of the Jamarat basin will result in a 25% improvement in the overall performance of the stoning process [43]. Sabilirrasyad et al. used Myo Armband for precise simulation of the stoning ritual by precisely determining the speed of throw for pelting stones at the pillars [44]. Ibadah et al. also carried out a similar study considering Jamarat basin, stoning performance, and improved pilgrim management [45]. Ilyas analyzed the shape of Jamarat pillars and concluded that current elliptical pillars outperform other shapes of pillars [46]. The proposed work also considered different pilgrim behaviors and other factors for the stoning ritual, such as hitting range, time to perform the ritual, and pilgrim spacing. The proposed model can be enhanced to include other complex pilgrim behaviors such as anxiety, fear, awe, and directional focus. Klüpfel proposed a general framework for emergencies in large-scale events and showed its effectiveness using three scenarios, including stoning the devil ritual [47]. The study emphasizes the importance of simulation settings selected by a user and their impact on the effectiveness of simulation. Mahmood et al. performed a similar study and compared various crowd evacuation strategies in emergencies in general and the stoning ritual in the Islamic pilgrimage in particular [37]. Al-Kodmany evaluated the Jamarat bridge comprehensively by considering various simulation models, analysis techniques, and pilgrim exit behaviors in an emergency [48]. The simulation models used by the authors include Legion and Myriad2 simulation models. Three behaviors of pilgrims in case of an emergency are analyzed. A pilgrim may choose to exit the Jamarat bridge area through the nearest exit, random exit, or the most popular exit, that is the exit preferred by most of the pilgrims. Additionally, the proposed simulation combines three techniques: network analysis, spatial analysis, and agent analysis.

With the recent advancements in artificial intelligence and machine learning techniques, some researchers have proposed solutions based on such techniques for crowd monitoring, crowd management, and congestion avoidance and control. Alazbah and Zafar used convolutional neural networks to detect congestion from live video of Jamarat bridge and warn the pilgrims with traffic-signal-like lights [49]. Taha et al. also employed convolutional neural networks for detecting the geographic location of pilgrims and helping in crowd management by identifying hotspots [50]. Habib et al. proposed an improved solution using Faster-RCNN (region-based convolutional neural networks) with an Inception V2 feature extractor [51]. Feldman et al. have provided an excellent review of the latest research in crowd management during Islamic pilgrimage [5]. **Table 1** presents a summary of the related works discussed above.

Table 1. Summary of proposals for pilgrimage rituals

Ref.	Year	Coverage of pilgrimage rituals	Technology proposed/used	Comments
[51]	2021	All rituals	Faster RCNN with Inception V2 feature extractor	The data set used for training the model is of modest size, resulting in low accuracy and precision.
[26]	2021	All rituals	Virtual reality	The proposed model can be used for the training of pilgrims before coming to the city of Makkah.
[35]	2021	Tawaf	Enhanced social force and crowd control models	The enhanced social force model is a generalized model used in several application domains.
[50]	2021	All rituals	Convolutional neural network	The proposed model suffers from low performance.
[34]	2020	Tawaf	Social force and agent and agent-based modeling	Comparison of two main categories of simulation models
[45]	2020	Stoning the devil	Human mobility model	The proposed model can help in better organization of the pilgrims.
[44]	2019	Stoning the devil	Myo Armband	The work helps in visual aspects of simulation with little impact on decision making.
[49]	2019	Stoning the devil	Convolutional neural networks	Image processing techniques performed on live video footage of the area warn the pilgrims against congestion.
[36]	2019	Kissing of the black stone	Auto-activated barriers	The proposed model does not cover any mandatory ritual of pilgrimage.
[28]	2018	All rituals	3D animation	The proposed solution can be used as a training mechanism for pilgrims coming to the city of Makkah.

[37]	2017	All rituals in the grand mosque	Agent-based simulation	An evacuation model is proposed that can be used in an emergency in the grand mosque.
[46]	2013	Stoning the devil	Agent-based simulation	A basic model is proposed with different pilgrim behavior and critical factors affecting the ritual of stoning the devil.
[48]	2011	Stoning the devil	Agent-based simulation, network analysis, spatial analysis, and agent analysis	The proposed model comprehensively analyzes the Jamarat bridge and pilgrim exit behavior.
[32]	2011	Tawaf	Agent-based modeling	The proposed model does not capture several essential behaviors of pilgrims, such as anxiety, fear, and joy.
[43]	2011	Stoning the devil	Agent-based simulation	The study has limited application as it needs significant structural changes.
[22]	2010	All rituals	Agent-based simulation	The proposed simulation framework can be used for the training of pilgrims.
[33]	2008	Tawaf	Analysis of pedestrian movement through the use of Global Positioning System and Geographic Information Systems	The recommendations have already been implemented
[31]	2007	Tawaf	Multi-agent simulation	The simulation results need to be verified with real-world data
[47]	2007	Stoning the devil	Multi-agent simulation	A general framework for emergencies in large-scale events is proposed.
[41]	2003	Stoning the devil	A new layout design for the Jamarat bridge	The study refers to the old design of the Jamarat bridge.
[42]	2003	Stoning the devil	Mathematical modeling and computer simulation	The study refers to the old design of the Jamarat bridge.
[30]	1997	Tawaf	A spiraling path around Kaaba	Needs significant changes to the existing infrastructure
[40]	1991	Stoning the devil	Multi-agent simulation	The study refers to the old design of the Jamarat bridge.

3. Proposed Model

Pedestrian simulation is a complex problem that needs careful consideration of various design parameters and aspects. The specific requirements of the ritual of stoning the devil make it even more challenging. The proposed simulation model for the ritual of stoning the devil comprises the following components.

- Basic pedestrian simulation model
- Locomotion model
- Social distancing model
- Stoning the devil ritual model
- Simulation evaluation measures

The details of these components follow.

3.1. Basic pedestrian simulation model

Chen et al. propose a pedestrian simulation framework based on the pedestrian agent, environment, and interaction with other agents [52]. The pedestrian agent senses its environment, processes information, moves within the environment, maintains its task list, makes decisions, communicates with other agents, and maintains a knowledge base. **Fig. 2** shows these basic building blocks of a pedestrian simulation model. In our proposed model, every pilgrim is an agent, and the area on the Jamarat bridge is the environment. Pilgrims sense the environment, i.e., pillars, walls, entry and exit points, and other pilgrims in the Jamarat area. They maintain information about the stoning process and task list, i.e., the number of pillars processed and the remaining pillars. Pilgrim movement behavior is another core simulation component discussed in the locomotion model subsection. Pilgrims make several decisions during the simulation, e.g., walking, maintaining social distance, and the stoning process. Knowledge base refers to other simulation aspects, such as the concepts of time and distance, which are discussed below.

3.1.1. Managing distance, time, and walking speed in pedestrian simulation

As stated above, pedestrians or agents are a core component of simulation. Environmental elements such as walls, pillars, ingress, and egress are also treated as agents. Hence, even simulation problems of modest complexity need to manage a massive number of agents. Simulating the same problem on different platforms with varying hardware specifications can produce different results. It makes it challenging to manage time in a simulation. The ritual of stoning the devil has stringent time requirements. Hence, precise measurement of time is crucial in our simulation model. As time, distance and speed are closely related, we present a solution considering these three factors.

Mapping real-life distance to a simulation model on a display screen is straightforward. One meter of length on the ground is considered to be equivalent to two patches on the screen. Depending on underlying hardware and screen characteristics, one patch may occupy any number of pixels on the screen.

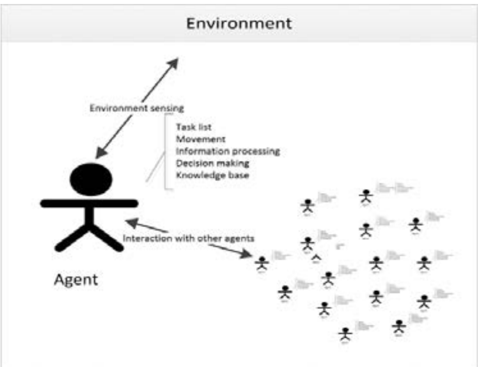

Fig. 2. Basic building blocks of pedestrian simulation

In the following, we explain how the pedestrian speed of pilgrims was adjusted in the model. Forde & Daniel analyzed the walking speed of 2937 pedestrians in various age groups at un-signalized midblock crosswalks [53]. **Table 2** summarizes the findings of their study.

Table 2. Average walking speed by age groups [53]

Age Group	Age (years)	Average speed (m/s)
Teenage	13-19	1.45
Young adults	19-30	1.55
Middle age	31-60	1.45
Older	> 60 but not classified as "elderly or physically disabled"	1.09
Elderly or physically disabled	> 60 and classified as "elderly or physically disabled"	1.04

As the pedestrian density is very high during the pilgrimage, a more careful approach is required for measuring pedestrian walking speed. Dridi analyzed video footage of pilgrims and used the block matching method to estimate the walking speed of pilgrims [54]. **Table 3** summarizes the walking speeds of various pilgrim groups as estimated by the study.

Table 3. Mean pedestrian speeds of pilgrims [54]

Pedestrian Pilgrim Group	Mean Pedestrian Speed (m/s)
Male	1.37
Female	1.22
Younger male	1.48
Older male	1.2
Younger female	1.32
Older female	1.12

The study concludes that a mean pedestrian speed of 1.33 m/s is appropriate for design purposes. Although this finding could be used for designing our simulation, we did our best to gather as much data as possible to design our model. According to the official statistics, 57% males and 43% females attended pilgrimage in 2017 [55]. Using this knowledge, we adjusted the walking speed of pilgrims in our model. Instead of using exact speeds, we use speed ± 10% to define a range of speed. Hence, the walking speed of male pilgrims was set to 1.23 – 1.51 m/s and that of female pilgrims to 1.10 – 1.34 m/s. As every two patches on the screen are equivalent to one meter of distance, a male pilgrim can be made to move forward by 2.46 – 3.02 patches in one simulation iteration to achieve the desired speed. It is to be noted that the speed of every pilgrim is fixed at the time of creation.

Calculating time in the simulation becomes straightforward once we have defined distance and speed.

$$Time = Distance/Speed \quad (1)$$

3.2. Locomotion model

A locomotion model is the heart of the pedestrian simulation. Many researchers have studied the walking behavior of pedestrians and formalized it into mathematical models. Some of the well-known locomotion models include the cellular automaton model [56], social force model [57], ordinary different equation-based models [58], velocity-obstacle-based model [59], optimal steps model [60], gradient navigation model [61], and behavioral heuristic model [62]. Zönnchen et al. have concisely reviewed various locomotion models [63]. We have extended the behavioral heuristic model to simulate the ritual of stoning the devil.

As the name implies, the behavioral heuristic model is based on cognitive heuristics used by pedestrians. The model starts with simplistic behaviors and builds more complex behaviors using these simple steps.

Algorithm 1: Step_or_wait_heauristic( )

```
Anticipate step towards target
If (LeadsToCollision)
    | Stay at the current position
Else
    | Take a step
End If
Return
```

Algorithm 2: Tangential_evasion_heauristic( )

```
Anticipate step towards target
If (LeadsToCollision)
    | Determine tangential step closer to the target
    | If (LeadsToCollision)
    |     | Determine another tangential step
    |     | Step_or_wait_heauristic( )
    | Else
    |     | Take a step
    | End If
Else
    | Take a step
End If
Return
```

Algorithm 3: Sideways_evasion_heauristic( )

```
Anticipate step towards target
Tangential_evasion_heauristic( )
If (LeadsToCollision)
    | Determine sideways step closer to the target
    | If (LeadsToCollision)
    |     | Choose another sideways step
    |     | Step_or_wait_heauristic( )
    | Else
    |     | Take a step
    | End If
Else
    | Take a step
End If
Return
```

3.3. Social distancing model

The primary objective of the proposed model is to analyze the impact of social distancing on the pilgrimage. This analysis may help the relevant authorities to optimize the number of pilgrims and resource allocation. We have considered two measures for implementing social distancing in the pilgrimage. Firstly, the number of queues determines the inter-queue spacing between pilgrims. Secondly, intra-queue spacing ensures specific spacing between pilgrims in the same queue. However, pilgrims cannot be expected to walk in unison because of the dynamic space on the Jamarat bridge. Hence, it is unrealistic to assume that intra-queue spacing can be guaranteed.

Ntounis et al. estimated the minimum amount of space required for a person to maintain social distance in various scenarios [64]. The study concludes that the minimum area required for a person to maintain 2, 1.5, and 1 m of social distance in outdoor commercial space is 12, 9, and 6 m^2, respectively. Although the findings cannot be directly applied to our simulation model because of the unique requirements of the study, they provide a general baseline. We have used several settings for social distancing in our study, as detailed in the experimentation section.

3.4. Stoning the devil ritual model

The basic pedestrian simulation model, locomotion model, and social distancing model provide a foundation for developing the model for stoning the devil ritual. **Fig. 3** shows the flowchart of the proposed model. The steps of the flowchart are detailed below:

1. First of all, the simulation environment is initialized with the global parameters. These parameters include the total number of pilgrims to be created during the simulation run, inter-queue spacing, intra-queue spacing, time for performing the stoning ritual, congestion threshold, and visual aspects of the simulation.
2. A batch of pilgrims is added to the simulation at the given rate in every iteration.
3. Every pilgrim in the simulation moves forward by the sideways evasion heuristic algorithm at the specified speed.
4. When a pilgrim reaches within a pillar's hitting range, the pilgrim is set to wait for the specified time, thus simulating the ritual of stoning the devil.
5. All pilgrims unable to move forward for the specified time are counted towards congestion.
6. After performing the stoning ritual on all three pillars, a pilgrim quits the Jamarat bridge area through an exit ramp.

3.5. Simulation evaluation measures

We are interested in two measures related to the Jamarat bridge in this study. Throughput refers to the rate at which pilgrims leave the Jamarat bridge after performing the stoning ritual. Congestion is a vital evaluation measure commonly used in the pedestrian simulation. Congestion refers to the number of pedestrians per unit area [65]. An area is considered congested if the number of pedestrians in that area exceeds a certain threshold. Considering the specific requirements of this study, where the number of pilgrims is extremely high around the Jamaraat pillars, we redefine congestion as the percentage of pilgrims unable to move forward for a certain threshold. In our study, we have considered this threshold to be 15 seconds.

4. Experiments and results

We have used NetLogo, a general-purpose simulation platform, to implement our proposed model. The model has many user-defined parameters. The first such parameter is the number of pilgrims. The Ministry of Hajj in Saudi Arabia has announced to allow 60,000 pilgrims this year. It makes it 12,000 pilgrims/floor of Jamarat bridge as it comprises five floors. Hence, the number of pilgrims in the simulation was set to 12,000 in all experiments. The congestion threshold was set to ten seconds, i.e., a pilgrim is considered part of congestion if he/she cannot move forward for ten seconds. We considered the time to perform the stoning ritual as 15 seconds. We performed experiments for several values of inter-queue and intra-queue spacing values. We discuss our findings below.

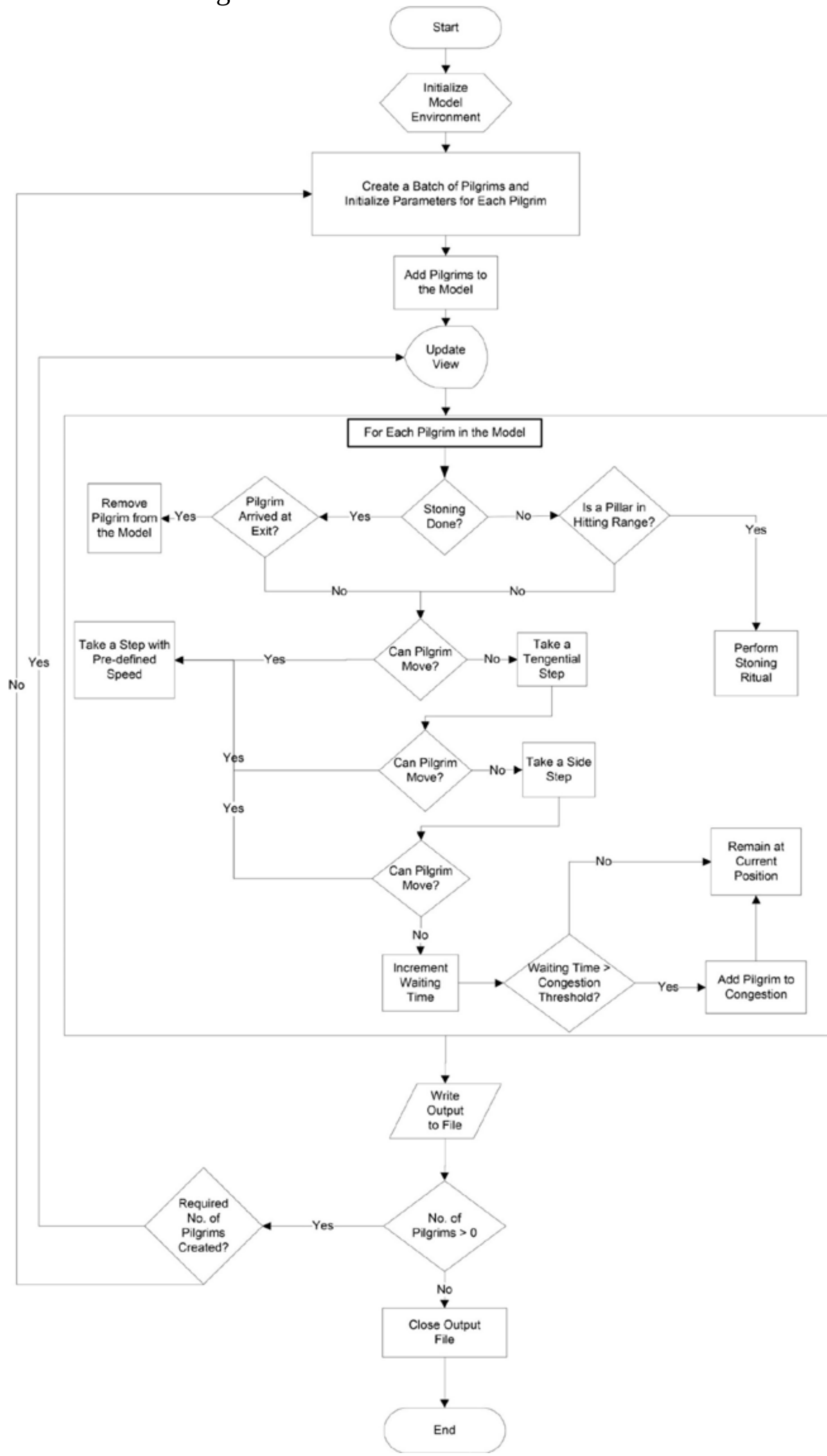

Fig. 3. Flow chart of the proposed model

4.1. Impact of intra-queue spacing on congestion

The first experiment in this study measures the impact of intra-queue spacing on congestion in the Jamarat bridge area. Intra-queue spacing refers to the spacing between two pilgrims in the same queue. We experimented with various spacings between pilgrims, including 1 m, 1.5 m, 2 m, and 2.5 m. Intuitively, intra-queue spacing has a reverse relationship with congestion. As shown in **Fig. 4,** the minimum spacing of 1 m between pilgrims resulted in a maximum of 18% congestion, while the congestion was reduced to 0.5% by maintaining a 2.5 m spacing between the pilgrims. However, it must be noted that inter-queue spacing is also a vital parameter in measuring congestion. Hence, both parameters must be evaluated to estimate optimal design parameters.

4.2. Impact of inter-queue spacing on congestion

Inter-queue spacing refers to the distance between adjacent queues in the Jamarat bridge area. We experimented by dividing the area into 10, 15, 20, 25, and 30 queues. **Fig. 5** shows values of congestions measured with these values of inter-queue spacing. Intuitively, the maximum inter-queue spacing, i.e., the minimum number of queues, produces the minimum pilgrim congestion in the area. As the number of queues increases, congestion increases in a linear fashion. However, it must be noted that congestion is not the only design criterion. The authorities also need to consider throughput when making such operational decisions. In the following, we show the impact of inter-queue and intra-queue spacing on the throughput of the structure.

4.3. Impact of intra-queue spacing on the throughput

Fig. 6 shows the impact of intra-queue spacing on the throughput. The maximum throughput observed is 82.86 pilgrims/s with a spacing of 1 meter between adjacent pilgrims. The throughput decreases linearly with increasing space between pilgrims, with the lowest peak throughput of 32.37 pilgrims/s with a spacing of 2.5 meters between adjacent pilgrims.

4.4. Impact of inter-queue spacing on throughput

Our last experiment observed the impact of the number of queues on the throughput. The results in **Fig. 7** show a peak throughput of 82.86 pilgrims/s for 30 queues as the maximum throughput achieved. The throughput decreased as the number of queues was decreased. The lowest peak throughput was achieved with ten queues at 32.37 pilgrims/s.

4.5. Analyzing Congestion and Throughput Simultaneously

As congestion and throughput have an inverse relationship, we need to find values for intra-queue and inter-queue spacing between pilgrims that achieve the best compromise between both measures. **Fig. 8** shows a scatter plot of all inter-queue and intra-queue spacing combinations used in this study and the peak congestion and throughput values achieved for each combination. The ideal combination is the one to the bottom right of the chart, i.e., a combination producing maximum throughput and minimum congestion. A visual inspection of the chart reveals that the combination of 25 queues and a 1.5 meter spacing between adjacent pilgrims achieves a peak throughput of 78.24 pilgrims/s and peak congestion of 3.12%. The combination of 15 queues and one-meter spacing is a close second choice with a maximum throughput of 74.99 pilgrims and a peak of 2.67 % congestion. The spacing combination of 15 queues and 2.5 m intra-queue spacing produced the worst results with the maximum throughput of 43.98 pilgrim/s and 7.75% for maximum congestion.

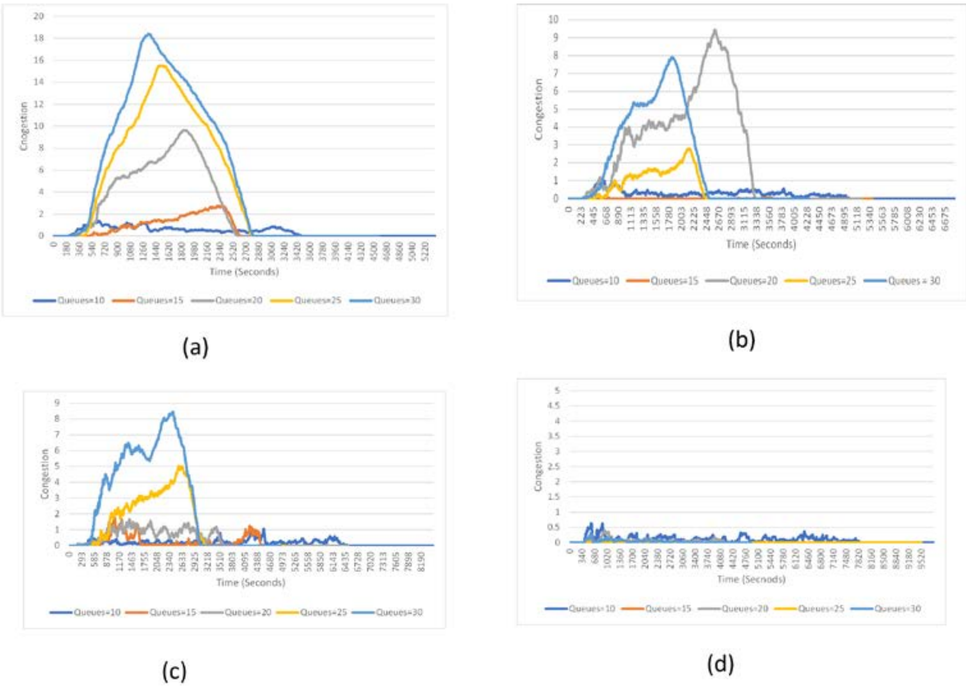

Fig. 4. Impact of intra-queue spacing on congestion with (a) 1 m, (b) 1.5 m, (c) 2 m, and (d) 2.5 m

5. Discussion

We have proposed a simulation model to analyze the impact of social distancing on throughput and congestion in the Jamarat bridge area. After analyzing several spacing combinations, we conclude that the combination of 25 queues and 1.5 m intra-queue spacing between adjacent pilgrims results in optimal throughput and congestion. These findings can help the Ministry of Hajj in Saudi Arabia better plan and manage the pilgrimage. However, pedestrian simulation models cannot guarantee to capture human behavior accurately. Hence, the results must be evaluated carefully before implementation.

We have defined congestion as the percentage of pilgrims unable to move forward for at least 15 seconds. A change in this definition will have an impact on the results of this study. Similarly, there is no data available regarding the time to perform the ritual of stoning the devil. Our results are based on the assumption of 15 seconds/pillar. A change in this parameter may also affect the results. Another limitation of the study is regarding queueing behavior of pilgrims. Although the study incorporates some randomness in pilgrim movement after performing one pillar's stoning, most pilgrims return to the same queue after stoning one pillar. More scientific data is required to understand the queueing behavior of pilgrims and use it in the simulation. The walking speed of pilgrims poses another challenge in the queueing process. We have used variable walking speeds for individual pilgrims, thus resulting in some pilgrims overtaking other pilgrims and violating intra-queue spacing. We need to study this phenomenon further to implement intra-queue spacing. As the pilgrims usually move in groups, strict implementation of queueing and spacing is a daunting task. Finally, the presence of pilgrims in wheelchairs may hinder queueing implementation.

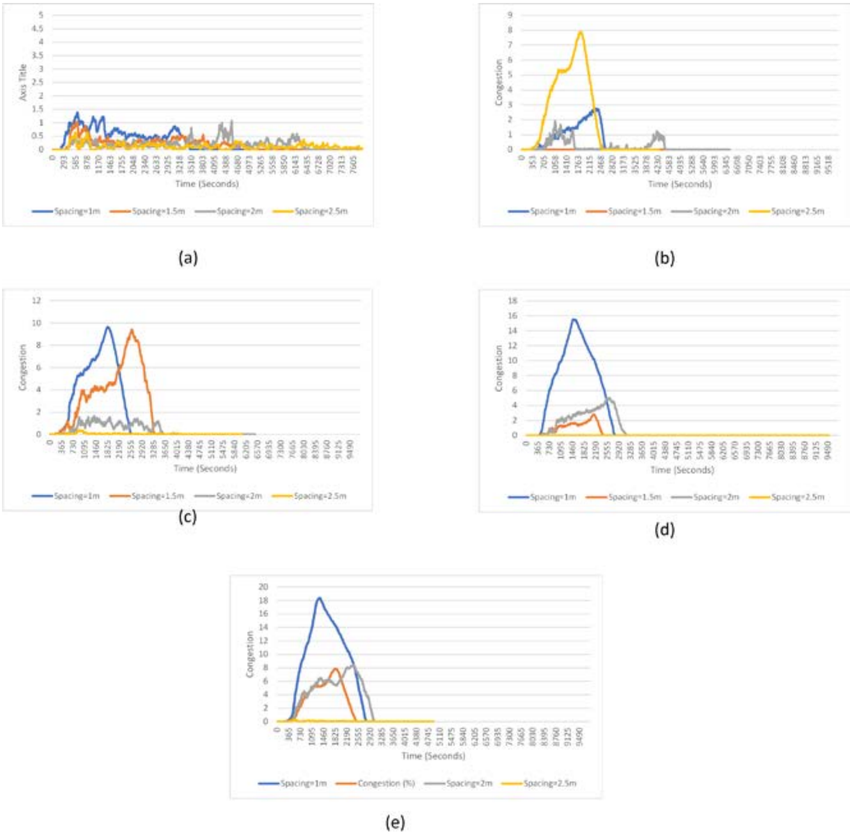

Fig. 5. Impact of inter-queue spacing on congestion with (a) 10, (b) 15, (c) 20, (d) 25, and (e) 30 queues

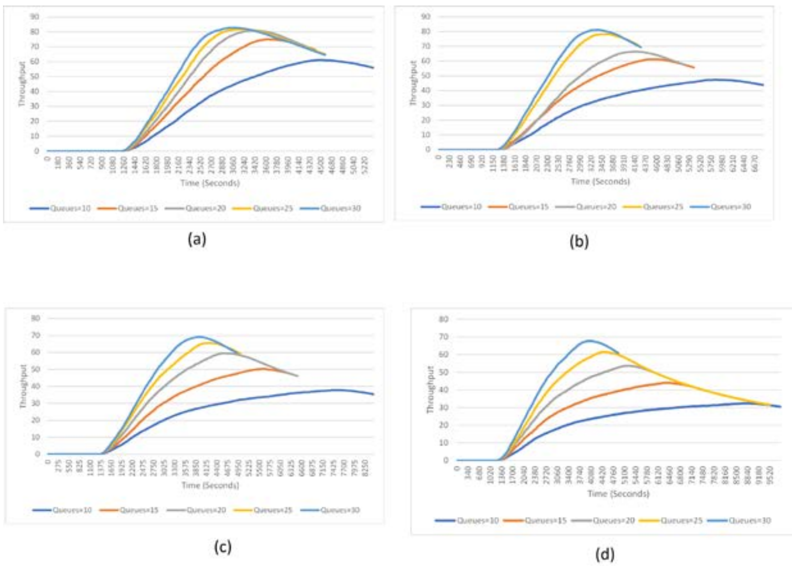

Fig. 6. Impact of intra-queue spacing on throughput with (a) 1 m, (b) 1.5 m, (c) 2m, and (d) 2.5 m

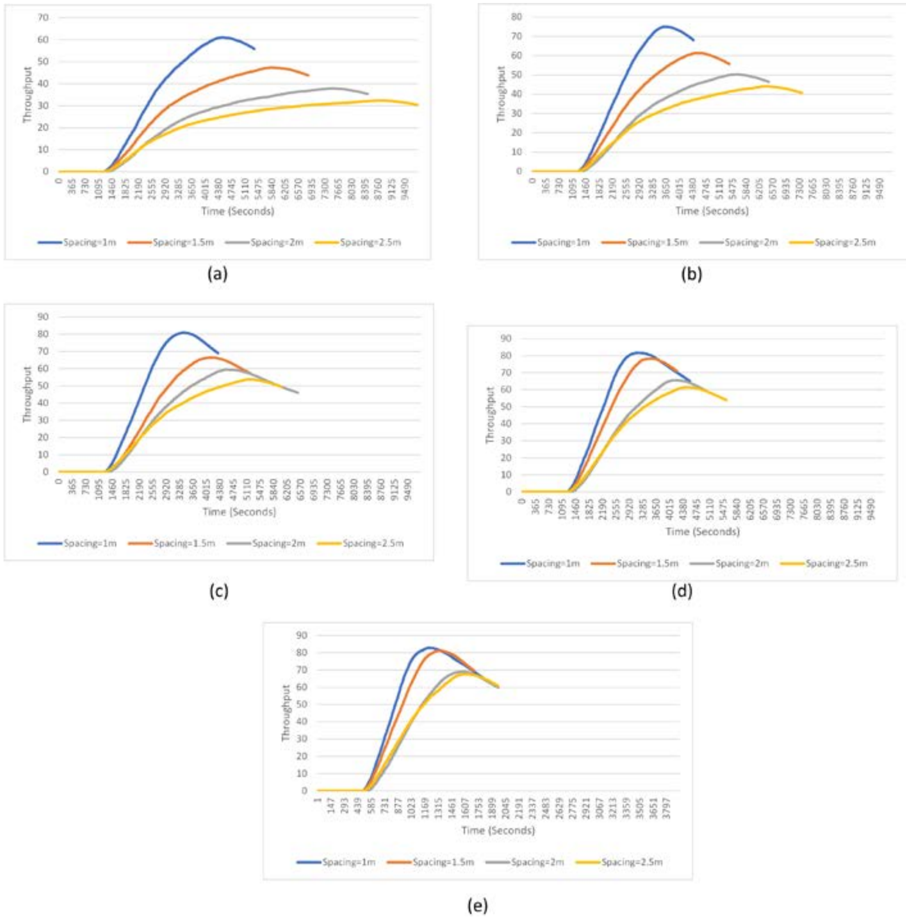

Fig. 7. Impact of inter-queue spacing on congestion with (a) 10, (b) 15, (c) 20, (d) 25, and (e) 30 queues

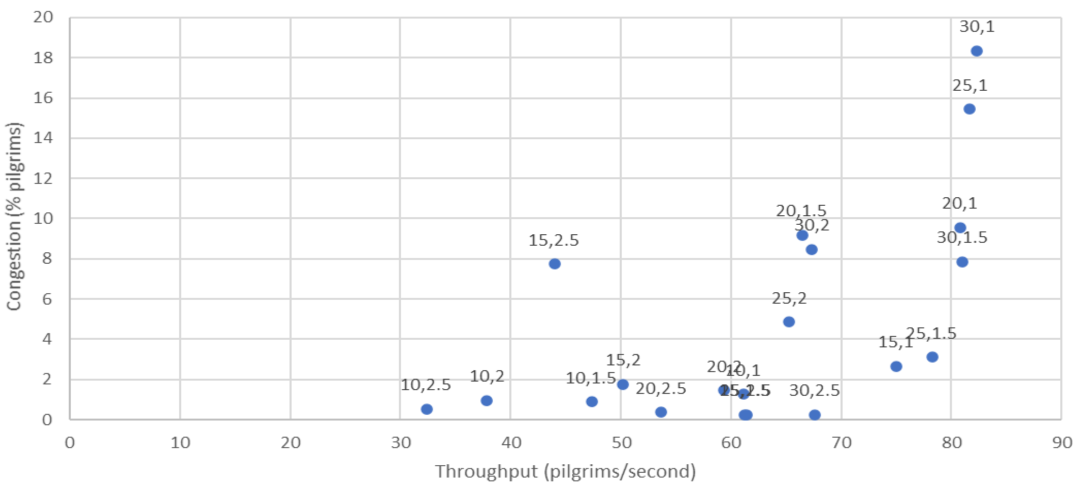

Fig. 8. Impact of inter-queue and intra-queue spacing on congestion and throughput; a value of (15, 2.5) represents the spacing combination of 15 queues and 2.5 m spacing between adjacent pilgrims

Model Availability

The simulation model has been developed in the NetLogo modeling platform. The proposed model, along with the entire code and raw data, is available for download on Github through the following link: https://github.com/Qazi-Mudassar-Ilyas/Jamarat-social-distancing

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