

## **MANAGING HAJJ CROWD COMPLEXITY: SUPERIOR THROUGHPUT, SATISFACTION, HEALTH, & SAFETY**

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### **ABSTRACT**

*Mass gatherings (MGs) are common phenomena with diverse crowd types and inherent problems, which need to be managed according to their level of complexity and potential of fatal outcomes. As such, for simple recurring MGs it is pragmatic to provide public health and safety through legislation and guidelines; whereas, complex infrequent MGs require specialized research and management. The Agent-Based Modeling and Simulation (ABMS) technique can provide insight into complex MGs by modeling micro level participant behavior to simulate emergent crowd behavior. The complex annual Hajj MG with its challenging Tawaf ritual is modeled using the ABMS technique to explore the impact of crowd characteristics, facility layout, and management preferences on emergent crowd performance with respect to throughput, satisfaction, health, and safety. The Tawaf ABMS simulator developed is called TawafSIM, which is the most comprehensive Tawaf simulator across multiple dimensions. It calculates eight metrics for Tawaf performance, which includes one for throughput, three for satisfaction, one for health, and three for safety. It is the only Tawaf simulator to estimate satisfaction and spread of infectious disease. It conducts 42 simulation experiments in 12 categories, which generate emergent, tipping point, expected, and counter intuitive behaviors. It recommends a default scenario as the recommended decision along with a small subset of alternative scenarios, which provide above average Tawaf performance. It generates a Tawaf Crowd Management Guide to understand Tawaf crowd dynamics and pursue above average Tawaf performance under different conditions.*

**Keywords:** *Crowd simulation, agent-based modeling and simulation, mass gathering medicine, Hajj, Tawaf, decision support system, operations management*

### **1 INTRODUCTION**

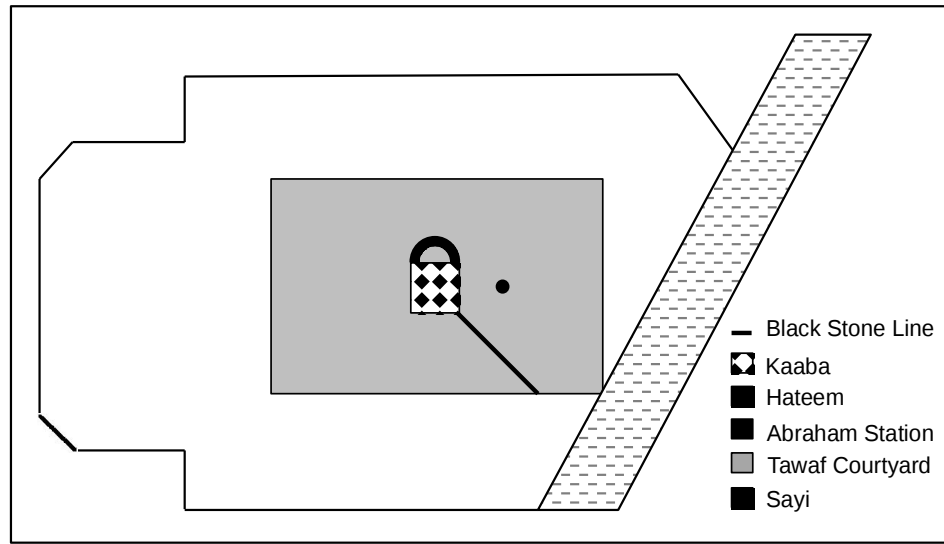
Mass gatherings (MGs) are common phenomena with diverse crowd types and inherent problems, which need to be managed according to their level of complexity and potential of fatal outcomes. First, although, there is no agreed upon definition for a MG, using the common characteristics identified in Al-Tawfiq & Memish (2012), Hines (2000), and Zeitz et al. (2009), a MG is defined as a large assembly of people at a specific time and place. This broad definition implies MGs are common phenomena that can take place among others at sports, entertainment, leisure, political, cultural, and religious events, which can occur at most public locations including transportation, shopping, entertainment and education venues. Second, the broad diversity of MGs is partially due to the different crowd types as reported in Zeitz et al., which include ambulatory, spectator, participatory, dense, and hostile. Third, according to the historical review of MGs in Al-Tawfiq & Memish and Hines, MGs inherently have the potential for injuries, deaths, medical emergencies, illness, and increasingly global outbreaks of infectious disease, which Al-Tawfiq & Memish and Soomaroo & Murray (2012) attribute to high crowd density, restricted access points, limited crowd control, lack of sufficient on-site medical response, and increase of global travel to and from MGs. Fourth, all MGs do not have high complexity or high potential for fatal outcomes, which is why well-documented historical MGs as in Al-Tawfiq & Memish usually include only the larger complex MGs, which include Olympics, Hajj, and World Youth Day. Finally,

according to Hines, public legislation and safety guides currently outline legal requirements and best practices for MG health and safety requirements but should be enhanced with specialized inter-professional initiatives. As such, for simple recurring MGs it is pragmatic to provide public health and safety through legislation and guidelines; whereas, complex infrequent MGs require specialized research and management to provide adequate public health and safety.

The Agent-Based Modeling and Simulation (ABMS) technique as explained by North & Macal (2007) can model complex MGs to identify the impact of crowd characteristics, facility layout, and management preferences on emergent crowd performance with respect to throughput, satisfaction, health, and safety. First, the ABMS framework models micro-level behavior of individual system components to simulate macro-level emergent outcomes. During the ABMS process, a large number of combinations for management choices and environmental factors are considered, which lead to the identification of poor and superior choices. In particular, an agent is a decision-making entity in the complex adaptive system with a set of attributes and behavioral characteristics. The attributes define what the agent is, such as, agent objective. While agent behavior define what the agent does, which includes: (i) decision rules to select actions, (ii) adaptive capability to learn from experiences, (iii) perception capability to sense its surroundings, and (iv) internal model to project possible consequences of decisions. Second, the emergent system behavior materializes through five steps executed for each agent: (i) evaluate current state, (ii) determine what to do, (iii) execute the action chosen, (iv) evaluate results of the action, and (v) adjust rules based on results. Finally, ABMS approach is useful when: (i) the problem has a natural representation consisting of interacting agents, (ii) there are decisions and behaviors that can be defined discretely, (iii) it is important that agents adapt and change their behavior, and (iv) it is important that agents have dynamic relationships with other agents, and agent relationships form and dissolve. As such, the ABMS technique is suitable to model individual participants in a complex MGs to determine how the MG policies affect the emergent crowd dynamics.

The Tawaf ritual at the Hajj is an example of a complex MG, which can be modeled using the ABMS technique to explore the impact of pilgrim crowd characteristics, Masjid al Haram courtyard layout, and Hajj authority management preferences on emergent Tawaf crowd performance with respect to throughput, satisfaction, health, and safety. First, the Hajj is the annual pilgrimage to Makkah in Saudi Arabia, which is an obligation on all Muslims at least once in their lifetime if financially capable where the reward for a properly accepted Hajj is having all the past sins of the pilgrim forgiven. Second, the Hajj is not only one of the oldest recurring MG but it is also one of the most complex. It involves 2-4 million pilgrims who come from all over the world with different languages and customs to make the annual pilgrimage during the last month of the Islamic calendar where the fixed duration rituals take place at four sites spread over 20 km, which take place over five to six days leading to traffic congestion at and between the Hajj sites. Third, during the Hajj, the Tawaf ritual, which takes place in Masjid al Haram in Makkah (Fig. 1), has the most challenging crowd dynamics where the crowd density can reach up to 7.5 pilgrims per 9.0 square feet leading to throughput, satisfaction, health, and safety issues. Specifically, the Tawaf involves circumambulating of the Kaaba counter-clockwise seven times, which can occur in the courtyard, second floor, or roof of Masjid al Haram where each round begins and ends at the Black Stone by touching or pointing to it. Finally, ABMS has the potential to model the micro-level behavior of the pilgrims to simulate emergent crowd behavior to provide superior: (i) throughput by processing the 2-4 million pilgrims in the required 48-hour

duration,



**Fig. 1: Masjid al Haram layout.**

(ii) satisfaction by providing a peaceful environment to concentrate on the act of worship, (iii) health by reducing the spread of infectious disease during the Tawaf and spread back to home countries, and (iv) safety by reducing the chances for casualties. As such, the ABMS of the complex Hajj MG's Tawaf ritual can help explore the impact of crowd characteristics, facility layout, and management preferences on Tawaf performance.

The rest of the paper is organized as follows. Section 2 discusses the related work with respect to crowd modeling approaches and Tawaf specific research. The implementation of the TawafSIM simulator is discussed in section 3, which includes key assumptions, models, and programming procedures. Section 4 addresses the simulation scenarios observations, which cover 12 categories with a total of 42 scenarios along with the identification of the scenario categories with high, medium, and low impact to Tawaf performance. Next, section 5 discusses the verification and validation of TawafSIM. Finally, section 6 presents the results from the simulations with respect to recommended scenario, emergent crowd behavior, and guideline for Tawaf crowd management.

## 2 RELATED WORK

This section begins with a review of crowd modeling techniques, which include: social forces model, cellular automata model, rule based models, and agent-based models. Then five important Tawaf crowd research studies are summarized. The first paper suggests a redesign to the Tawaf process to enhance performance. The second study analyzes the Tawaf movement using GPS. The next two papers simulate the Tawaf crowd using Cellular Automata approach, while the last paper uses ABMS approach.

In Sarmady et al. (2007), the authors claim micro-level movement behavior is important part of crowd modeling, which can be accomplished in three main approaches. First, in social forces model, the person's motion is subject to social forces (e.g. collision avoidance). This approach can simulate low and high crowd density but does not result in realistic behavior on its own because people do not completely follow laws of physics, instead they decide to stop and start. As well, this approach is computationally complex. Second, in cellular automata (CA) models, a uniform grid of cells, each with a local state is used. The models have rules to compute the state of each cell as a function of the previous state and state of adjacent cells. Although this approach is fast due to a simple algorithm, since each cell holds one person, it usually does not effectively simulate dense crowds. Third, in rule-based models, specific

predetermined rules for pedestrian movement are used, which work well in low-density crowds but not in high density because the models do not consider collision detection, pushing, and repulsion. A fourth approach to crowd modeling that is not mentioned in the paper is ABMS, which models each individual in the crowd using a set of attributes and behavioral characteristics that are then used to simulate emergent crowd behavior when the individuals in the crowd interact with each other.

In Al-Haboubi & Selim (1997), the authors present a design to minimize congestion around the Kaaba during the Tawaf ritual by eliminating cross traffic. They state pilgrims who have completed the seven rounds of Tawaf are spiraling outward cause cross traffic with those pilgrims who are spiraling inward in the early stage of the Tawaf, which causes safety, distraction, and delays. Although the authors suggest cross traffic reduction solutions based on scheduling pilgrim admittance, constructing a second floor around Kaaba in the courtyard, and limiting maximum pilgrim capacity, they recommend building a spiral path around the Kaaba, which encircles it seven times, then at the Kaaba there is a ramp leading to underground dispersion area. Although their recommended solution eliminates the cross traffic problem, the spiral design makes the spiritual Tawaf ritual appear more like an amusement park ride, which is probably why it has not been adopted.

In Koshak & Fouda (2008), the authors analyze pilgrim movement in the Tawaf areas using GPS units rather than the traditional crowd analysis technique based on human visual observations using video recordings. The research identifies seven zones in the Tawaf area with different velocities. As well, they confirm a pilgrim performing Tawaf on the roof completes one round before a pilgrim performing Tawaf in the courtyard even though the distance around the roof is significantly longer due to the extreme congestion in the courtyard. Although the analysis is outdated due to facility changes and uses only four GPS units, the seven velocity zones identified may be used to validate Tawaf simulation models that model similar Tawaf crowd conditions.

In Abdelghany et al. (2005), the authors simulate the Tawaf crowd using a cellular automata approach with features to model dynamic adjustment of pilgrim destination and movement direction as conditions change along with pilgrim congestion aversion preference. The research conducts five experiments to see the impact on Tawaf throughput and average pilgrim speed by varying levels for congestion, spatial demand loading, cross traffic, free-flow speed, and congestion aversion, which confirm the intuitive anticipated results from such experiments. Although this research illustrates the capability of their model using five experiments, the model limits Tawaf performance metrics to only throughput and average speed as well the limited experiments seem to confirm known results rather than identify unanticipated emergent behavior which could not be anticipated without the model.

In Sarmady et al. (2007) (2008) (2011), the authors simulate the Tawaf crowd using a cellular automata approach with features to model pilgrim macroscopic movement using static path tables between possible destinations along with pilgrim characteristics for age, gender, health, energy, fatigue, speed, and stress. They claim the simulation run with random initial pedestrian positions is comparable to Tawaf video footage. Although the model captures more pilgrim characteristics than Abdelghany et al. (2005), it lacks a comprehensive set of experiments and Tawaf performance metrics as well its macro movement algorithm is constraint by static path tables.

In Curtis et al. (2011), the authors simulate the Tawaf crowd using ABMS approach with features to model pilgrim age and gender as well use a finite state machine for pilgrim behavior and collision avoidance algorithm for interaction with neighbors. The model measures crowd density, velocity, and throughput to explore the impact of gender and age on Tawaf throughput, which show 100% young male and female crowds have throughput of 58,600 and 52,700 pilgrims per hour respectively. Although the model uses the more natural

ABMS approach, the research lacks a comprehensive set of Tawaf performance metrics and experiments.

### **3 TAWAFSIM IMPLEMENTATION**

The Tawaf simulator developed in this paper using the ABMS approach is called TawafSIM (Khan, 2013), which models the micro-level behavior of Hajj pilgrims performing the Tawaf ritual in order to explore the impact of crowd characteristics, facility layout, and management preferences on Tawaf performance with respect to throughput, satisfaction, health, and safety.

#### **3.1 Assumptions**

TawafSIM is influenced by the modeling philosophy that believes a system with known problems with pragmatic solutions should not be modeled to determine the decisions that lead to superior system performance. Instead, first the known problems should be replaced with pragmatic new policies, which can then be simulated to determine the decision parameters, which lead to superior performance. With respect to the Tawaf ritual, it is well known that the disturbance to the natural circular crowd flow leads to negative consequences for throughput, satisfaction, health, and safety. In particular, the disturbance is due to (i) mini mob at the Black Stone and to a much lesser degree the crowd buildup at the Kaaba walls; (ii) non uniform flow of pilgrims due to rectangular shape of Kaaba; and (iii) extreme high crowd density. As such, the existing Tawaf crowd dynamics should not be modeled; instead, the known disturbance can be eliminated by adopting the following new pragmatic policies that (i) place a temporary moveable circular barrier around the Kaaba during Hajj only and (ii) maintain a maximum number of pilgrims in the courtyard.

#### **3.2 Models**

The Tawaf area is modeled as a circular area with the Kaaba in the center where the minimum and maximum radius is 37 and 130 feet respectively with a grid resolution of 1 by 1 foot. Although the Tawaf can occur on the main courtyard, second floor, and roof of Masjid al-Haram, only the courtyard is modeled since it is the most challenging Tawaf area. Since it is assumed the Kaaba will be completely surrounded with a temporary barrier, the minimum Tawaf radius is 37 feet; whereas, the maximum courtyard radius is 130 feet. Furthermore, the rest of the rectangular courtyard is not modeled to leave room for pilgrims entering and exiting the courtyard and also to prevent the rectangular shape of the courtyard to generate resistance to circular movement of the crowd. As a comparison, the Tawaf crowd models in Abdelghany et al. (2005) and Sarmady et al. (2011) model the maximum Tawaf courtyard radius to be 158 feet (48 meters).

The individual pilgrim attributes are modeled for size, gender, manners, speed, strength, health, and desire to touch Kaaba/Black Stone. First, in TawafSIM each pilgrim is modeled as 1 by 1 foot square shape, which is also the resolution of the Tawaf courtyard. This pilgrim size intuitively represents the smallest space that most people may be forced to assume, which is consistent with Hines (2000) where the Hajj crowd density can reach up to 7.5 people per 9 ft<sup>2</sup> (9 people per m<sup>2</sup>). Nevertheless, there is significant discussion on the correct anthropomorphically representation of a wide range of human body shapes, which in Still (2000) is determined to be 1.6 by 1.0 feet (50 by 30 cm); however, a 1 by 1 foot (30 by 30 cm) equivalent shape is used instead for computational simplicity to represent the area of the shape. Whereas in Al-Haboubi (2003), the Muslim bodies sizes are listed with the maximum body size determined to be 1.8 by 1.1 feet (54 by 35 cm). As well, in Sarmady et al. (2010) the pilgrim size is chosen to be 1.3 by 1.3 feet (40 by 40 cm), which matched their grid resolution. Second, in TawafSIM the pilgrim attributes for manners, strength, and desire to touch the Kaaba/Black Stone are modeled as low, medium, or high states, which have to be estimated until Hajj authorities conduct a pre- or post-Hajj survey to determine the percentage of each states. Third, in TawafSIM the maximum pilgrim speed attribute is modeled to be 1, 2, or 3 feet per second, which is based on measuring a range of people walking while

pretending to perform the Tawaf. The maximum 1 foot per second speed generally represents a pilgrim with slow walking speed due to age, fatigue, or other hardship; whereas 2 feet per second represents a typical healthy pilgrim concentrating on the Tawaf act of worship while the 3 feet per second generally represents a pilgrim concentrating more on finishing the Tawaf and less on the act of worship. There is significant discussion and difference of opinion on what the speed of a pedestrian should be for different walking scenarios. As a comparison, Al-Haboubi (2003) measured walking speed as 2.9, 2.2, and 1.7 feet per second as high, medium, and low speeds respectively. While in Al-Haboubi & Selim (1997) walking speed is reported to be 3.8 and 3.6 feet per second for men and women respectively. As well, the Tawaf crowd model in Abdelghany et al. (2005) uses 1.6 and 3.3 feet per second for slow and fast velocities respectively. Finally, in TawafSIM, the infected, immune, or susceptible states of a pilgrim's health attribute help determine how infectious diseases can spread from pilgrim to pilgrim during the Tawaf. The percentage of pilgrim population that is infected, immune, and susceptible during the Tawaf has to be estimated until Hajj authorities collect information from post-Hajj pilgrim questionnaire and information from the Hajj Medical record system.

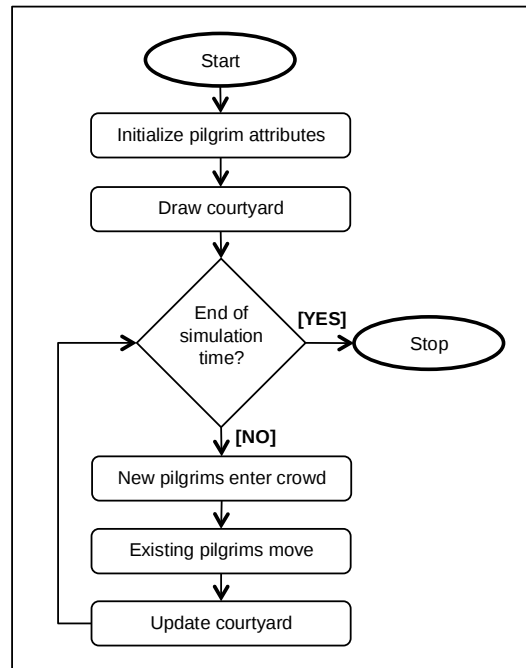
The individual pilgrim behaviors are modeled to allow each pilgrim agent to autonomously perform seven rounds around the Kaaba, which includes: (i) perceive its Moore neighbors in the Tawaf courtyard, which are the eight neighbors surrounding a central neighbor in a square lattice; (ii) evaluate its goals for number of rounds to spiral in, maintain circle, and spiral out based on attributes and environment; (iii) evaluate its desired next step location using macro-level spiral equation; (iv) select actual next step location from among the Moore neighbors of the desired next step location using micro-level decision rules; and (v) adapt new macro-level spiraling trajectory based on past experience.

### **3.3 Performance Metrics**

TawafSIM does not rely on the emergent crowd dynamic animation of the pilgrims in the courtyard, as it provides limited information; instead it develops a comprehensive set of eight metrics to measure the Tawaf crowd performance for throughput, safety, satisfaction, and health. To determine the Tawaf performance metrics, TawafSIM records for each pilgrim the data necessary to determine four categories of performance metrics. Throughput measures average pilgrim Tawaf time to complete each of the seven rounds along with number of pilgrims completing the Tawaf per hour. Satisfaction is based on three metrics: (i) percentage of time a pilgrim has to deviate from its desired macro-level spiral trajectory to avoid a collision or other undesirable crowd congestion situations, (ii) percentage of time a pilgrim is with 0 to 8 Moore neighbors, and (iii) percentage of time a pilgrim is with 0 to 8 opposite gender Moore neighbors. Health measures the percentage of time a pilgrim is with infecting Moore neighbors during its Tawaf duration. Safety is based on three metrics: (i) percentage of courtyard grids in low, medium, and high threat levels, (ii) highest density values for each courtyard grids, and (iii) percentage of time each courtyard grid is in high threat.

### **3.4 Program Flow**

The TawafSIM program flowchart, which is shown in Fig. 2 starts by initializing 90,000 pilgrims being simulated with their individual attributes. The distribution for each attribute, which is based on reasonable estimates and can be modified when accurate data is available, is presented in the next section. After initialization, the empty courtyard is displayed then the simulation is run for two hours of simulated time where for each simulated second, the following three tasks take place.



**Fig. 2: TawafSIM program flowchart.**

First, new pilgrims enter the Tawaf courtyard and are placed randomly on the Tawaf crowd boundary. In particular, the number of pilgrims allowed to enter the courtyard is based either on the management set pilgrim entry rate or the management set maximum courtyard capacity, whichever is lower. Additionally, for each pilgrim, its behavioral spiraling goals are determined for number of rounds to spiral in, maintain radius, and spiral out. As well, the behavior goals also include calculating the closest distance to the Kaaba the pilgrim will reach after the spiral in rounds are complete.

Next, each pilgrim moves to its new position using the macro-micro movement algorithm. First, the polar coordinates of the “desired next step location” are calculated using a macro-level spiral equation. In particular, the new theta value for moving the pilgrim in the counter clockwise direction is a function of the current radius value and the pilgrim’s speed; whereas, the new radius value is calculated using the new theta value in the spiral equation. Second, the “actual next step location” is selected from the Moore neighborhood of the “desired next step spiral equation location” using micro-level rules, which selects the Moore location with the lowest sum from the following three factors: (i) distance of the Moore location to the “desired next step spiral equation location” five-time steps in the future; (ii) number of neighbors of the Moore location; and (iii) number of opposite gender neighbors of the Moore location. Thus, if all the Moore locations are occupied then the pilgrim does not move for that time step; otherwise, it moves to the Moore location that has the lowest weighted value from these three factors.

Finally, after all pilgrims move to their next location, the courtyard grid is updated. Then these three steps continuously occur until the end of the simulation time is reached or all 90,000 pilgrims have finished the Tawaf at which time the simulation stops and the Tawaf performance metric data are saved to a file.

#### 4 TAWAFSIM SIMULATION OBSERVATIONS

TawafSIM is used to simulate 42 scenarios in 12 different categories. For each scenario, TawafSIM displays the animation of the emerging crowd and aggregates the data to calculate each of the eight Tawaf performance metrics, which are displayed as plots and tables. As well, all the results from the 12 scenarios are summarized in a single table.

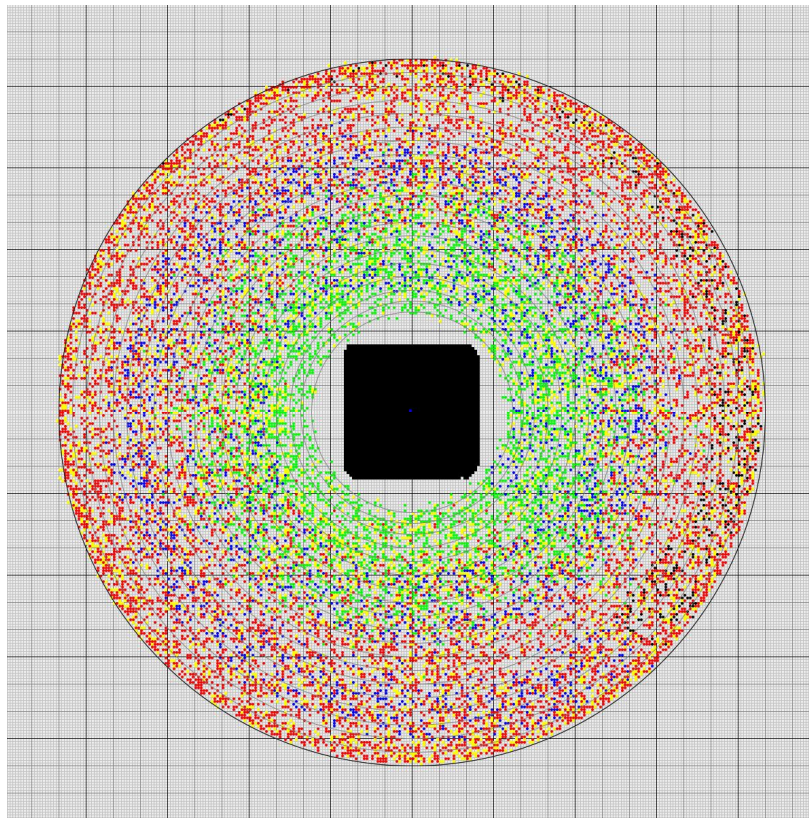
Table 1 shows the TawafSIM simulation parameters for the 42 scenarios including the default scenario used to determine the impact on the Tawaf performance metrics from gender, pilgrim rate of entry, courtyard access, maximum pilgrim capacity, manners, speed, strength, desire to touch Kaaba/Black Stone, Health, and degree of spiraling inward.

**Table 1: TawafSIM simulation parameters.**

| 12 CATEGORY OF SCENARIOS                     | 42 INDIVIDUAL SCENARIOS <sup>s</sup> |             |             |             |
|----------------------------------------------|--------------------------------------|-------------|-------------|-------------|
|                                              | Scenario #: Scenario Parameters      |             |             |             |
| 1. Gender (% male/female)                    | 2: 100/0                             | 3: 75/25    | 4: 25/75    | 5: 0/100    |
| 2. Constant Rate of Entry (pilgrims per sec) | 6: 10                                | 7: 15       | 8: 25       |             |
| 3. Bursty Rate of Entry (sec)                | 9: 300                               | 10: 600     | 11: 900     |             |
| 4. Entry Access (degrees)                    | 12: 90                               | 13: 180     | 14: 270     |             |
| 5. Maximum Pilgrims (#)                      | 15: 30,000                           | 16: 35,000  | 17: 40,000  |             |
| 6. Manners (% low/medium/high)               | 18: 100/0/0                          | 19: 0/100/0 | 20: 0/0/100 |             |
| 7. Speed (% low/medium/high)                 | 21: 100/0/0                          | 22: 0/100/0 | 23: 0/0/100 |             |
| 8. Strength (% low/medium/high)              | 24: 100/0/0                          | 25: 0/100/0 | 26: 0/0/100 |             |
| 9. Desire Touch Kaaba (%)                    | 27: 100/0/0                          | 28: 0/100/0 | 29: 0/0/100 |             |
| 10. Infecting (%)                            | 30:                                  | 31:         | 32:         | 33:         |
| 11. Immune (%)                               | 34:                                  | 35:         | 36:         | 37:         |
| 12. Round Farthest Spiral In (% round)       | 39: 0/0/0                            | 40: 0/0/100 | 41: 0/100/0 | 42: 100/0/0 |

<sup>s</sup>Each of the 42 individual scenarios have the same simulation parameters as the default scenario except for the single parameter identified above; where the default scenario has 60/40 male/female ratio; 20 pilgrims/sec rate of entry; 360 degree access; 25,000 max pilgrims; 25/50/25 low/medium/high ratio for manners, speed, strength, & desire touch Kaaba; 20/50/30 immune/susceptible/infecting ratio; and 24/33/42 Round 1/2/3 ratio.

As TawafSIM simulates each scenario, it visually displays the emergent crowd dynamics. Fig. 3 shows a snapshot of the Tawaf crowd where the dots represent the pilgrims while the color indicates their spiraling status. The red pilgrims are spiraling inward from the edge of the crowd boundary to generally the outer one half of the circles whereas the green pilgrims are maintaining their radius at circles closest to the Kaaba while the blue pilgrims are spiraling outward which become black pilgrims when they complete the seven rounds and spiral outward to exit the crowd. The yellow pilgrims are found throughout the crowd, which represent pilgrims that are distracted and have to change their desired macro-level spiral based trajectory due to other pilgrims and their preference for crowd aversion.



**Fig. 3: TawafSIM simulation animation snapshot.**

Although the crowd animation is interesting and provides a high level view of how the crowd emerges, it does not provide any details, which is why the details with respect to throughput, satisfaction, and health are provided by aggregating simulation data into plots like Fig. 4. This example figure for throughput metric clearly shows the impact of increasing maximum pilgrim capacity on not only throughput but on the individual seven rounds. Along with metrics for throughput, satisfaction, and health, TawafSIM also aggregates simulation data to generate a safety figure for each of the 42 scenarios as shown in Fig. 5. The top plot shows how the low, medium, and high threat levels change over the duration of the simulation. The left plot shows the highest pilgrim density per grid while the right plot shows what percent of time each grid remains in high threat. As well, the plots for each category are summarized in a table format. An example is shown in Table 2, which show the impact of each scenario in the maximum pilgrim capacity category on both the individual performance metric and the over all impact on the Tawaf. Finally, to comprehend how the 12 categories of scenario experiments impact individual and overall Tawaf performance, Table 3 summarizes the results.

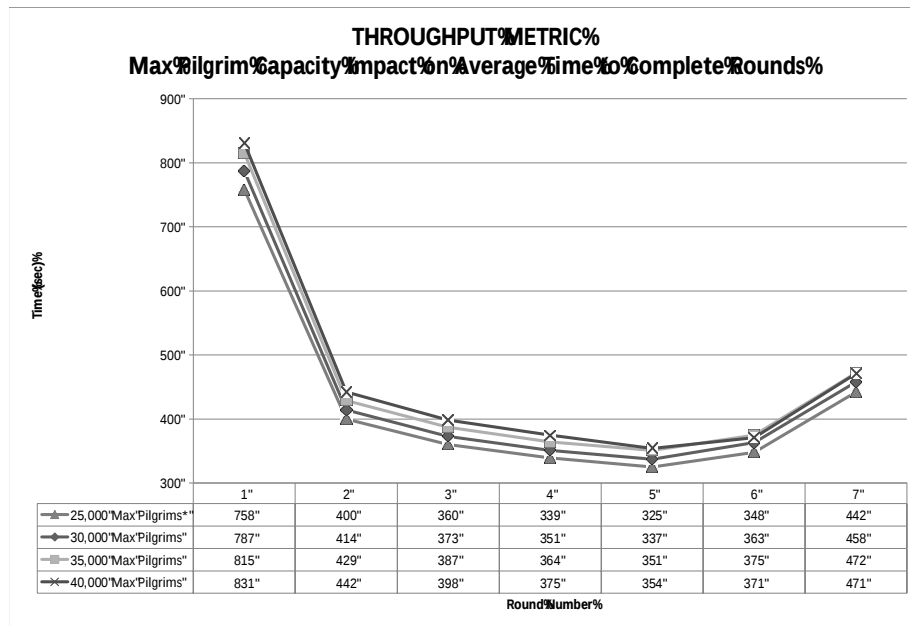


Fig. 4: Maximum pilgrim capacity scenarios impact on Throughput metric.

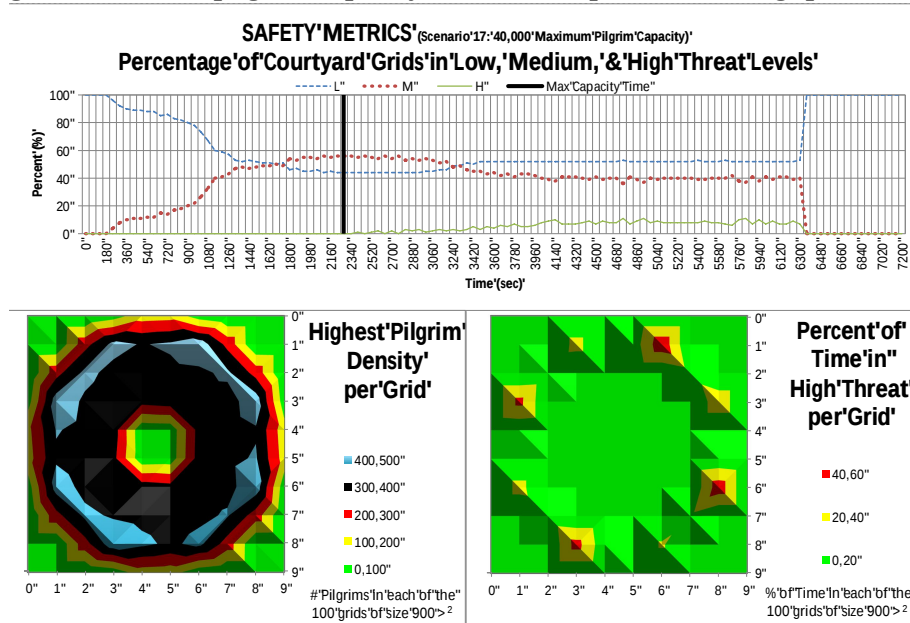


Fig. 5: Safety metric for 40,000 maximum pilgrim capacity scenario.

Table 2: Capacity category scenarios impact on Tawaf crowd performance.

| SCENARIO                    | THROUGHPUT               | SATISFACTION            |                      |                       | HEALTH              | SAFETY               |                    |                    | IMPACT ON TAWAF |
|-----------------------------|--------------------------|-------------------------|----------------------|-----------------------|---------------------|----------------------|--------------------|--------------------|-----------------|
|                             |                          | B <sup>2</sup>          | C <sup>3</sup>       | D <sup>4</sup>        |                     | F <sup>6</sup>       | G <sup>7</sup>     | H <sup>8</sup>     |                 |
| Default 25,000 pilgrims     | 30,283<br>n/a<br>n/a     | 27.6<br>0<br>n/a<br>n/a | 2.34<br>n/a<br>n/a   | 0.90<br>n/a<br>n/a    | 8.85<br>n/a<br>n/a  | 390<br>n/a<br>n/a    | 0<br>n/a<br>n/a    | 0<br>n/a<br>n/a    | N/A             |
| Scenario 15 30,000 pilgrims | 35,031<br>(+16%)<br>Med+ | 29.1<br>0<br>(+9)       | 2.54<br>(9%)<br>Low- | 0.93<br>(+3%)<br>Low- | 8.95<br>(+1%)<br>No | 411<br>(+5%)<br>Low- | 3<br>(+3%)<br>Low- | 6<br>(+6%)<br>Low- | LOW (1.8)       |

|                                       |                             |                                  |                            |                             |                       |                            |                           |                              |                      |
|---------------------------------------|-----------------------------|----------------------------------|----------------------------|-----------------------------|-----------------------|----------------------------|---------------------------|------------------------------|----------------------|
|                                       |                             | %)<br>Low-                       |                            |                             |                       |                            |                           |                              |                      |
| <b>Scenario 16</b><br>35,000 pilgrims | 39,461<br>(+30%)<br>V.High+ | 29.3<br>0<br>(+6%)<br>%)<br>Low- | 2.64<br>(13%)<br>)<br>Med- | 0.99<br>(+10%)<br>)<br>Med- | 9.25<br>(+5%)<br>Low- | 445<br>(+14%)<br>)<br>Med- | 6<br>(+6%)<br>)<br>Low-   | 47<br>(+47%)<br>)<br>V.High- | <b>HIGH</b><br>(3.3) |
| <b>Scenario 17</b><br>40,000 pilgrims | 44,417<br>(47%)<br>V.High+  | 31.3<br>0<br>(13%)<br>)<br>Med-  | 2.81<br>(20%)<br>)<br>High | 1.05<br>(+17%)<br>)<br>Med- | 9.50<br>(+7%)<br>Low- | 466<br>(+20%)<br>)<br>Med- | 11<br>(+11%)<br>)<br>Med- | 55<br>(+55%)<br>)<br>V.High- | <b>HIGH</b><br>(3.5) |
| <b>IMPACT ON METRIC</b>               |                             | <b>ME D</b><br>(2.3)             | <b>ME D</b><br>(3.0)       | <b>MED</b><br>(2.7)         |                       | <b>MED</b><br>(2.7)        | <b>MED</b><br>(2.3)       | <b>HIGH</b><br>(4.0)         |                      |
|                                       | <b>V.HIGH</b><br>(4.3)      | <b>MED</b><br>(2.7)              |                            |                             | <b>LOW</b><br>(1.3)   | <b>MED</b><br>(3.0)        |                           |                              | <b>MED</b><br>(2.8)  |

<sup>1</sup>Pilgrims/hr<sup>2</sup>% Time Distracted<sup>3</sup># Neighbours<sup>4</sup># Gender Neighbours<sup>5</sup>% Time Exposed<sup>6</sup>Pilgrims/900 ft<sup>2</sup><sup>7</sup>% Grids in High Threat<sup>8</sup>% Time in High Threat**Table 3: Summary of each scenario category impact on Tawaf performance.**

| SCENARIO CATEGORY     | THROUGHPUT     | SATISFACTION   |                |                | HEALTH         | SAFETY         |                |                | IMPACT ON TAWAF |
|-----------------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|-----------------|
|                       | A <sup>1</sup> | B <sup>2</sup> | C <sup>3</sup> | D <sup>4</sup> | E <sup>5</sup> | F <sup>6</sup> | G <sup>7</sup> | H <sup>8</sup> |                 |
| <b>Spiral In</b>      | <b>HIGH</b>    | <b>HIGH</b>    | <b>HIGH</b>    | <b>V.HIGH</b>  | <b>MED</b>     | <b>MED</b>     | <b>LOW</b>     | <b>MED</b>     | <b>HIGH</b>     |
|                       |                | <b>HIGH</b>    |                |                |                | <b>MED</b>     |                |                |                 |
| <b>Speed</b>          | <b>V.HIGH</b>  | <b>HIGH</b>    | <b>LOW</b>     | <b>LOW</b>     | <b>MED</b>     | <b>HIGH</b>    | <b>LOW</b>     | <b>HIGH</b>    | <b>HIGH</b>     |
|                       |                | <b>MED</b>     |                |                |                | <b>MED</b>     |                |                |                 |
| <b>Max Pilgrims</b>   | <b>V.HIGH</b>  | <b>MED</b>     | <b>MED</b>     | <b>MED</b>     | <b>LOW</b>     | <b>MED</b>     | <b>MED</b>     | <b>HIGH</b>    | <b>MED</b>      |
|                       |                | <b>MED</b>     |                |                |                | <b>MED</b>     |                |                |                 |
| <b>Infecting</b>      | <b>NO</b>      | <b>NO</b>      | <b>NO</b>      | <b>NO</b>      | <b>V. HIGH</b> | <b>NO</b>      | <b>NO</b>      | <b>NO</b>      | <b>LOW</b>      |
|                       |                | <b>NO</b>      |                |                |                | <b>NO</b>      |                |                |                 |
| <b>Rate of Entry</b>  | <b>LOW</b>     | <b>MED</b>     | <b>LOW</b>     | <b>NO</b>      | <b>LOW</b>     | <b>NO</b>      | <b>NO</b>      | <b>NO</b>      | <b>LOW</b>      |
|                       |                | <b>LOW</b>     |                |                |                | <b>NO</b>      |                |                |                 |
| <b>Circular Entry</b> | <b>LOW</b>     | <b>LOW</b>     | <b>NO</b>      | <b>NO</b>      | <b>NO</b>      | <b>NO</b>      | <b>NO</b>      | <b>NO</b>      | <b>NO</b>       |
|                       |                | <b>LOW</b>     |                |                |                | <b>NO</b>      |                |                |                 |
| <b>Gender</b>         | <b>NO</b>      | <b>NO</b>      | <b>NO</b>      | <b>V.HIGH</b>  | <b>NO</b>      | <b>NO</b>      | <b>NO</b>      | <b>NO</b>      | <b>NO</b>       |
|                       |                | <b>LOW</b>     |                |                |                | <b>NO</b>      |                |                |                 |
| <b>Manners</b>        | <b>NO</b>      | <b>NO</b>      | <b>NO</b>      | <b>LOW</b>     | <b>NO</b>      | <b>NO</b>      | <b>NO</b>      | <b>NO</b>      | <b>NO</b>       |
|                       |                | <b>NO</b>      |                |                |                | <b>NO</b>      |                |                |                 |
| <b>Desire Touch</b>   | <b>NO</b>      | <b>LOW</b>     | <b>LOW</b>     | <b>LOW</b>     | <b>NO</b>      | <b>LOW</b>     | <b>NO</b>      | <b>NO</b>      | <b>NO</b>       |
|                       |                | <b>LOW</b>     |                |                |                | <b>NO</b>      |                |                |                 |
| <b>Strength</b>       | <b>NO</b>      | <b>NO</b>      | <b>NO</b>      | <b>LOW</b>     | <b>NO</b>      | <b>NO</b>      | <b>NO</b>      | <b>NO</b>      | <b>NO</b>       |
|                       |                | <b>NO</b>      |                |                |                | <b>NO</b>      |                |                |                 |
| <b>Immuni-</b>        | <b>NO</b>      | <b>NO</b>      | <b>NO</b>      | <b>NO</b>      | <b>NO</b>      | <b>NO</b>      | <b>NO</b>      | <b>NO</b>      | <b>NO</b>       |

| zation                      |                                           | NO                                  |                                    | NO |  |
|-----------------------------|-------------------------------------------|-------------------------------------|------------------------------------|----|--|
| <sup>1</sup> Pilgrims/hr    | <sup>2</sup> % Time Distracted            | <sup>3</sup> # Neighbours           | <sup>4</sup> # Gender Neighbours   |    |  |
| <sup>5</sup> % Time Exposed | <sup>6</sup> Pilgrims/900 ft <sup>2</sup> | <sup>7</sup> % Grids in High Threat | <sup>8</sup> % Time in High Threat |    |  |

## 5 TAWAFSIM VALIDATION

With regards to validation of TawafSIM, no model can claim it is 100% error free or 100% fully matches the real system; nevertheless, attempts are made to provide a high degree of confidence that TawafSIM is programmed correctly and matches the real Tawaf crowd behavior by following the guidelines for rigorous ABMS model development in North & Macal (2007) and Rand & Rust (2011).

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

With respect to confidence in matching real Tawaf crowd behavior, like most other complex social systems, the validation is subjective (North & Macal, 2007); however, the typical approach for validation is to show that the model produces sound insights and sound data based on a wide range of tests. First, practical validation involves validating TawafSIM input, output, processes, and agent behaviors. Second, case approach validation compares the 42 scenario simulations with empirical Tawaf data, other models, and subject matter experts. Third, model calibration calibrates TawafSIM macro- and micro-movement algorithms to known Tawaf crowd dynamics. Finally, parameter sweeping generates the range of results and behaviors the model is capable of producing, which shows TawafSIM produces sound implications and sound data.

## 6 TAWAFSIM RESULTS

Despite the effort made to validate the complex social behavior of the Tawaf crowd dynamics, before TawafSIM can be used for Tawaf crowd management, Hajj authorities need to calibrate TawafSIM with accurate Tawaf data and pilgrim behavior through additional specialized research studies (Abdelghany et al., 2005; Curtis et al., 2011). Nevertheless, the 42 simulation scenarios from TawafSIM in 12 categories provide significant insight into the Tawaf crowd dynamics and provide both specific and broad recommendations. Specifically, this section summarizes how crowd characteristics (i.e. gender, manners, speed, strength, desire to touch Kaaba, and spiraling inward), facility layout (i.e. circular entry access), and management preferences (i.e. pilgrim infecting level, pilgrim immunization level, rate of pilgrim entry, and maximum pilgrim capacity) impact Tawaf performance with respect to throughput, satisfaction, health, and safety.

### 6.1 Recommended Scenario

The analysis of the 42 scenarios reveal the default scenario allows pilgrims to complete seven rounds in 50 minutes and provides above average Tawaf performance when compared to other scenarios. Only three of the below eight metrics for the default scenario are significantly less favorable than other scenarios. First, default throughput of 30,283 pilgrims per hour is 39% lower than the highest value of 49,234 for scenario 23 (i.e. 100% high speed

scenario). Second, default percent time distracted of 27.60% is 52% higher than the lowest value of 18.10% for scenario 23 (i.e. 100% high speed scenario). Third, default percent time exposed of 8.85% is 19% higher than lowest value of 7.45% for scenario 6 (i.e. 10 pilgrims per second). As such, the default scenario parameters provide overall above average Tawaf performance when compared to the other scenarios.

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

## **6.2 Emergent Crowd Behavior**

The observations and analysis of the 42 scenarios help identify several noteworthy emergent crowd behaviors to better manage the Tawaf crowd, which include tipping point, expected, and counter intuitive emergent behaviors.

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

## **6.3 Guidelines for Tawaf Crowd Management**

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

1. Gender distribution for the pilgrim population does not have to be managed at any particular level. However, a dominant gender pilgrim population significantly decreases number of opposite gender neighbours while a single gender population eliminates opposite gender neighbours.
2. Pilgrim rate of entry can fluctuate between 15 to 25 pilgrims per second. However, 15 pilgrims per second rate is optimum and a rate of 10 pilgrims per second if necessary should be maintained for less than 15 minutes.

3. Courtyard circular entry access is optimum from 75% to 100%. Whereas, 50% access will have low unfavourable impact on only throughput while 25% access will have low unfavourable impact on overall Tawaf performance.
4. Maximum pilgrim capacity is optimum (i.e. meets minimum throughput requirement with best conditions for satisfaction, health, and safety) at 25,000 pilgrims, which is 50% of total Tawaf area. Whereas, 30,000 pilgrim capacity increases throughput moderately with unfavourable low impact on other metrics while pilgrim capacity of 35,000 to 40,000 has very high increase on throughput with medium unfavourable impact on other metrics.
5. Limit maximum pilgrim capacity to 82% of total Tawaf area with unobstructed circular path to limit maximum grids in high threat to 11%.
6. Pilgrim manners, strength, and desire to touch the Kaaba do not have to be managed at any particular level since each has at most a low unfavourable impact limited only to satisfaction.
7. Maintain high pilgrim speed, which has a significant favourable impact on throughput, satisfaction and health while a moderate unfavourable impact on safety; whereas, low pilgrim speed has a very high unfavourable impact on overall Tawaf performance.
8. Minimize percentage of infecting pilgrims through immunization and other infectious disease preventative measures to decrease the chance susceptible pilgrims get infected. However, for a given percentage of infecting pilgrims performing Tawaf, increasing immunization level of susceptible pilgrims does not decrease their exposure to infecting pilgrims.
9. Decrease exposure to infecting pilgrims by increasing pilgrim speed and decreasing pilgrim rate of entry. As well, avoid excess exposure by preventing homogenous low pilgrim speed and slow spiralling inward.
10. Avoid homogenous pilgrim population, which generally decreases Tawaf performance.

## **7 CONCLUSIONS**

The paper demonstrates that complex MGs can be modeled and simulated using ABMS to provide insight and recommendations for the impact of crowd behavior, facility layout, and management preferences on crowd performance with respect to throughput, satisfaction, health, and safety. As well, the paper shows specific insight and recommendations for the Tawaf ritual of the complex Hajj MG with respect to recommended decisions, emergent crowd behavior, and guidelines for Tawaf crowd management. Finally, the paper shows that mass gathering crowd complexity can be managed through crowd simulators that model comprehensive set of system features, performance metrics, and experiments.

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