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MODELING THE FLOW OF CROWD DURING TAWAF AT MASJID AL-HARAM

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ABSTRACT

Tawaf is one of the most important rituals of hajj or umrah performed by the Muslim pilgrims in Masjid Al-Haram yard, Makkah, Saudi Arabia. It consists of seven counterclockwise circulations around Ka'aba, a building situated in the middle of the yard. Large crowds of pilgrims performing Tawaf during peak seasons need to be investigated towards providing a safe and robust crowd management plan. Although many studies have been reported, related to Tawaf, but many of them focused on animation and behavior during Tawaf. There have been limited studies addressing human crowd during Tawaf from queuing system and optimization perspectives. This research modeled the Tawaf activities based on queuing system using discrete-event simulation, ARENA. Alternative crowd management policies were studied and their performances were compared using three criteria namely, density, service rate and average time in the system. Important design factors such as pilgrim inter-arrival time, group size, availability of space and switching behavior during Tawaf were investigated. The simulation results suggest that switching lane during Tawaf is the most significant factor in crowd density development and reduce efficiency of the queuing system. The proposed Tawaf model using separation, spiral path and timely scheduled the incoming pilgrims has resulted in the best performance among the investigated models. The techniques used in this study, is potentially applicable to other huge crowd gathering such as in theme parks, public transportation hubs and sports events.

Keywords: *Tawaf, crowd management, crowd modelling, queuing theory, simulation.*

1.0 INTRODUCTION

Tawaf is one of the rituals that Muslim must perform upon entering the *Masjid Al-Haram*, in *Makkah*, Saudi Arabia. During the peak times such as hajj, tens of thousands of pilgrims perform *Tawaf* in the courtyard of this Mosque. The timing and space limitation and large crowd of people, make the crowd management a challenging task where Safety is one of the most important issues when dealing with such a large crowd. Three steps should be taken to develop safer crowd, which are crowd modelling, crowd monitoring and crowd management [1]. Crowd modelling investigates how, where, when and why crowds arrive, move around and leave an event/venue. Crowd monitoring is monitoring of the arrival flow rates, how the queues build up, areas of high crowd density and different types of crowd behaviour, both normal and emergency. Crowd modelling and crowd monitoring are both essential to develop a safe and robust crowd management plan. In previous researches, crowd during *Tawaf* was studied from diverse points of view [2, 3, 4, and 5]. However, our review identified that crowd during *Tawaf* from safety and queuing efficiency aspects only addressed by Al-Hanoubi and Selim [6]. Most

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of the other researches from computer science and mathematics schools conducted studies focusing on density estimation and developing virtual representation of crowd behaviors. There is lack of studies on the flow of pilgrims during *Tawaf* from queuing theory perspective.

This paper presents investigation to evaluate the effect of various crowd formation factors and their interaction in congestion development towards improving the flow and reducing the congestion. The study is limited to the crowd movement in the main court of *Masjid Al-Haram*.

The rest of this paper is organized as follows. Section 2 discusses previous works in the area of crowd modeling approaches and *Tawaf* simulation. In section 3, the approach to the current study is described, while section 4 presents the results. Section 5 discusses the key findings and finally section 6 concludes the paper.

2.0 PREVIOUS WORKS IN CROWD MODELING

In this section, previous works in crowd simulation and modeling are discussed. Some prior crowd simulation models for *Tawaf* are also highlighted.

2.1 Crowd Simulation Models

Crowd was defined as a single entity whose members have the same motives and/or continuously engage in the same actions [7]; while Widyarto [2] defined it as a large number of people that were considered together. However, Zhou *et al.* [8] believe that a crowd is not simply a collection of individuals. The behavior of an individual may be affected by others in the crowd, which may depend on various physiological, psychological and social factors.

Large crowds are a normal part of operation in many public venues such as railway stations, fairgrounds, leisure centers and sports stadiums. Overcrowding in places like concerts, stadiums or pilgrimage locations might sometimes cause injury or even loss of life. From the commercial point of view, large numbers of customers may be desirable, but excessive crowding and poor crowd management can lead to crushing, injury and even death and at the very least to such anxiety and stress that visitors decide not to come again or recommend a visit to others. Maintaining the safety of crowd in these places is therefore of prime importance. In addition, increasing the safety performance of the buildings and structures has always been an important concern.

In addition to the personal suffering such disasters, the accompanying adverse publicity, loss of revenue, compensation payments, insurance costs and possible prosecution can have a long-term effect on organizations. Disasters should not happen provided those responsible, at all levels, pay careful attention to managing crowds safely. Overcrowding might lead to crowd disasters and cause loss of life and serious injuries. Several major incidents that had happened in the past are shown in Table 1.

Table 1: Recent crowd incidents [8]

Date	Incidents
18th December 2005	42 Homeless people were trampled to death and 37 were injured in a stampede during the distribution of flood relief supplies at a shelter in Chennai, India.
31st August 2005	Hundreds dead pilgrimage stampede in Iraq.
12th January 2006	363 dead in *Jamaraat* Bridge when large seas of pilgrims were moving forth to the *Jamaraat* at noon to perform the stoning ritual in Makkah, Saudi Arabia.
1st January 2007	Hundreds hurt in New Year revelry in Philippines.
4th August 2008	150 Hindu worshippers were crushed to death in a stampede at a hill temple in northern India.
14th November 2009	60 People hurt in crush to see JLS at Christmas lights event in Birmingham, England.

There had been an extensive literature on crowd simulation and many techniques had been proposed. Nine major systems of modeling have been found in literatures. Flocking system also known as Rule-Based model was the earliest system of crowd modeling [9]. In this model, agents can seek goal, move as a group and can avoid collision. Each boid (bird-oid) acts independently, keep track of its position and orientation by perceiving the local dynamic environment and usually adopt a conservative approach by avoiding contact, however, it has only local information and does not know about the global environment. Thus the agent perceives its neighboring flock-mates and obstacles and applies “wait” rules to enforce ordered crowd behavior without the need to calculate collision detection and response.

Behavioral system that was developed by Tu and Terzopoulos [10], utilize reusable characters is especially beneficial to the movie industry and computer games. In Chaos model [11], the crowds are set as independent moving agents that have general motion pattern. The Agent- Based model could capture variability of different characteristics and heterogeneity to motion but since individual agent must be considered separately, comparing its state with every others resulting in complexity [12]. Social Forces Model was based on repulsion and tangential forces to simulate interactions between people and obstacles, realistic “pushing” behaviors and variable flow rates [13]. Hybrid System which was a combination between Flocking agent-based and behavior systems, required modeling of crowd information and hierarchical structure, also concerning its distribution among groups and structure to provide interaction with groups of agents during the simulation in real-time [14].

Fluid Dynamic Model or Cellular Automata that can handle obstacles and pedestrian was noted acting like a combination of groups of people [15]. Cognitive Model mixed with rule-based model to achieve more realistic behaviors of pedestrian was reported by Shao and Terzopulus [16]. Another pedestrian simulation system called cell and portal graphs was presented by Pettre *at al*. [17]. In this system, information can be embedded in high-level representation of the virtual environment to achieve real-time crowd simulation. However, as space dimension or complexity of the configuration gets larger, the number of cells required might increase too much to be practical.

2.2 Tawaf Simulation

A few studies have been reported on crowd flow in the *Mataf* area in the Masjid al Haram. A spiral movement path was proposed by Al-Haboubi and Selim [6] in the *Tawaf* area to decrease congestion and hence increase the throughput and the safety of the system. The proposed design involved building a spiral path around *Ka'aba* which encircles it seven folds where the entrance of the path is at the outermost fold and the completion of the *Tawaf* is at the innermost fold leading down a ramp to an underground tunnel.

Widyarto and Abd- Latif [18] investigated the relationship between fractal pattern and crowd behavior–to imitate the crowd paths [18]. Zarita et al. [4] proposed a model for circumambulating the *Ka'aba* in SimWalk software. In their model, waiting areas were placed in specified areas to guide the pedestrians to walk seven times around the *Ka'aba*.

Sarmady *et al.* [3] presented a cellular automata model for the simulation of the pilgrim's circular *Tawaf* movement based on a discrete-event model to simulate the actions and behaviors of the pilgrims. The study investigated whether structural changes to the area or the operational elements would create a significant gain in the throughput of the system.

A framework for simulating complex behaviors exhibited by pilgrims performing the *Tawaf* was proposed by Curtis *et al.* [19]. By coupling a high-level finite-state-machine with a low-level local collision avoidance algorithm, they modeled a range of behaviors such as: circumambulating the *Ka'aba*, queuing to touch the Black Stone, entering and exiting the *Mataf* floor, and pausing to perform *Istilam*.

Based on the above review, it is identified that there is a research gap between crowd modeling and crowd optimization techniques. Although many works have been reported in the area of *Tawaf* simulation, none of the reviewed models addressed *Tawaf* as an optimization queuing problem.

3.0 Methodology of the Investigation

According to Adnan *et al.* [20], seven steps should be considered in simulation procedure namely, i. Recognition, ii. Problem formulation, iii .Model construction, iv. Data collection, v. Model solution, vi .Model reliability and validity and vii. Interpretation of result, implications and sensitivity analysis. This study adopted these steps.

Tawaf consists of a set of prescribed rites in assigned locations around *Ka'aba*. Performing this ritual within limited time, would results in crowded scenario of extraordinary magnitude. Such bottlenecks can turn into congestion around *Ka'aba* and may lead to accidents. High density, varying velocity and complex motions make *Tawaf* a challenging task [19]. In this study, the problem was modeled in such a way to address these factors. The crowd density throughout the *Tawaf* area would often vary and can reach as high as eight pilgrims per square meter near the *Ka'aba* [21]. Such extremely high density could restrict the movement of the pilgrims. The velocity of the pilgrims in *Tawaf* area may vary depending on many factors such as their distance from the *Ka'aba*, proximity of structures on the floor or congestion caused by special events. Different types of crowd flows can be observed during *Tawaf*. At any given time, pilgrims would try simultaneously to stand still to kiss the Black Stone located at the corner of the

Ka'aba, circumambulate the *Ka'aba*, or attempt to move orthogonally to the circular flow, inwards, toward the *Ka'aba*, or outwards, towards the exit, preventing purely circular flow.

To formulate the problem the layout of the *Tawaf* area and the sequence of *Tawaf* should be considered. Figure 1 shows *Tawaf* procedure graphically. Pilgrim walks seven counter-clockwise circles around the *Ka'aba* and *Hateem*. Each circle starts in front of the black stone indicated as the start region [19].

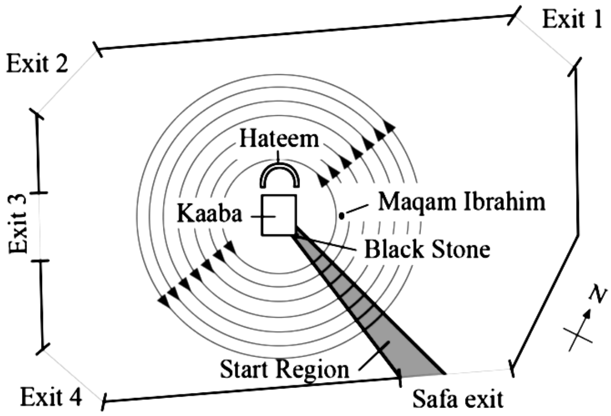

Figure 1: Tawaf Procedure, Seven Counter- clockwise circle [19]

The *Tawaf* Procedure is described below:

i. Pilgrims enter the *Tawaf* area and proceed towards the start region that is located at the *Ka'aba*'s eastern corner. This landmark serves as the start and finish point of each circumambulation.
ii. After reaching the region in front of the Black Stone, pilgrims perform *Istilam* (a short prayer said facing the *Ka'aba).*
iii. The pilgrim walk, in counter-clockwise direction, around the *Ka'aba* and *Hateem*.
iv. At the completion of each circumambulation, the pilgrims perform *Istilam* again.
v. At the end of seventh circle, the pilgrims perform a short prayer outside the *Tawaf* area, in behind the *Maqame Ibrahim* or any convenient location in the mosque. Some pilgrims may prefer to join the queue to kiss the Black Stone upon completion on the *Tawaf.*
vi. Pilgrims exit the *Tawaf* area. Zarita et al [4] noted that 61% of the pilgrims exit the *Tawaf* through the *Safa* exit in preparation for the next ritual.

A proposed model is formulated according to the above procedure, however, due to the variations that exist between different school of thoughts as well as for simplicity, details related to Steps 2, 4 and 5 are not considered in this study.

Conceptual Model of *Tawaf* area adopted from Sarmady *et al.* [3] is shown in Figure 2. Different sections of the *Tawaf* area in the *Masjid Al-Haram* court have different properties. Therefore, the *Tawaf* circle was divided into sub-sections to represent different speed-density. The *Ka'aba* walls, especially those parts that are in Section I4 are very favorable to pilgrims who would attempt to reach and touch the walls and pray in this section. Additionally, people move slower as they move close to *Ka'aba*. In Sections I4, M4 and O4, there is an arbitrary *Tawaf* start-finish line or area. Too many people in these sections may cause congestion in the area since pilgrims either starting their *Tawaf* or cross the *Tawaf* circumambulation for exits. The sections O1, O2, O3, M1, M2 and M3 were chosen for comparison since they lack of such congestion.

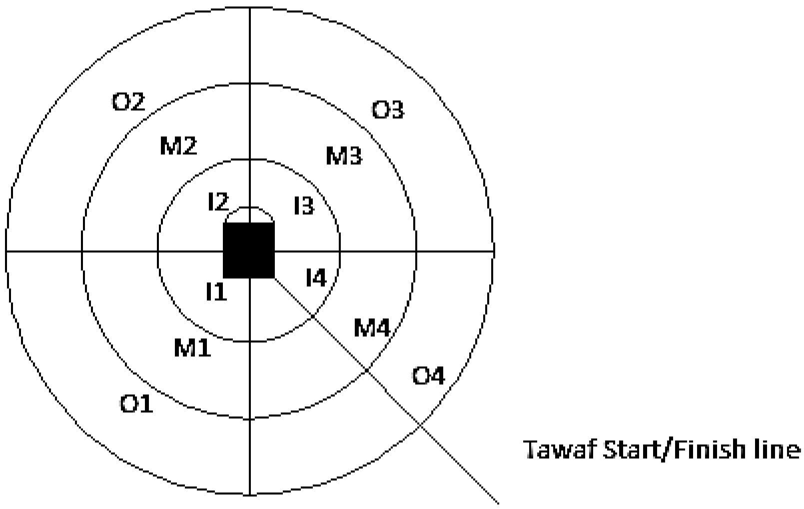

Figure 2: Conceptual model [3]

In the simulation model, each section of *Tawaf* area is represented with a Server as a single machine having specific cycle time according to section characteristics. Parts that enter the model represented the pilgrims or customers of the *Tawaf* queuing system. Customer characteristics such as speed and sequence of actions are shown by different attributes that either individual or batch of parts carry when entering the system. Machine cycle times and failures schedule, represent average process time and disturbance intervals that occur in each *Tawaf*. Other elements such as buffers, routes, stations, were used in the modeling.

A discrete event modeling tool, ARENA was chosen for this research. The simulation model describes the process that an "entity" experiences while flowing through or using the elements of the system [22]. In this study, system refers to *Mataf* or the *Tawaf* court. The entities are Pilgrims who perform the *Tawaf*. Pilgrims are discrete units that enter the system, flow through the system and then depart the system. Resources used by entities may constrain the flow of the entities in the system. In *Tawaf* system, the *Mataf* area and its sub-areas (sections) are the resource that 'give service' to pilgrims.

The nature of this study is that most of the real data are neither available nor collectable. As such reference and derived parameter values were used. The alternative models in this research were built incrementally based on Basic Model as a benchmark. The concept behind the Basic Model is to represent the *Mataf* by a queuing system that has several servers and several queues, as shown in Figure 3.

Each entity with its specific attributes namely gender, speed and size was generated according to Poisson distribution. They were stored in a buffer to be called randomly to the available queues. Queue capacities of servers were analyzed and upon availability of space in queues, each entity moved to first available server with priority given to the closest queue to *Ka'aba*. The queues of entities moved seven times in a specified route according to their attributes until they reached the finishing line in the seventh round. At this stage, entities were disposed. The movement rule was set in such a way to enable each entity to switch queues by choosing the closest server to *Ka'aba* whenever more than one section with free space was available in its defined route.

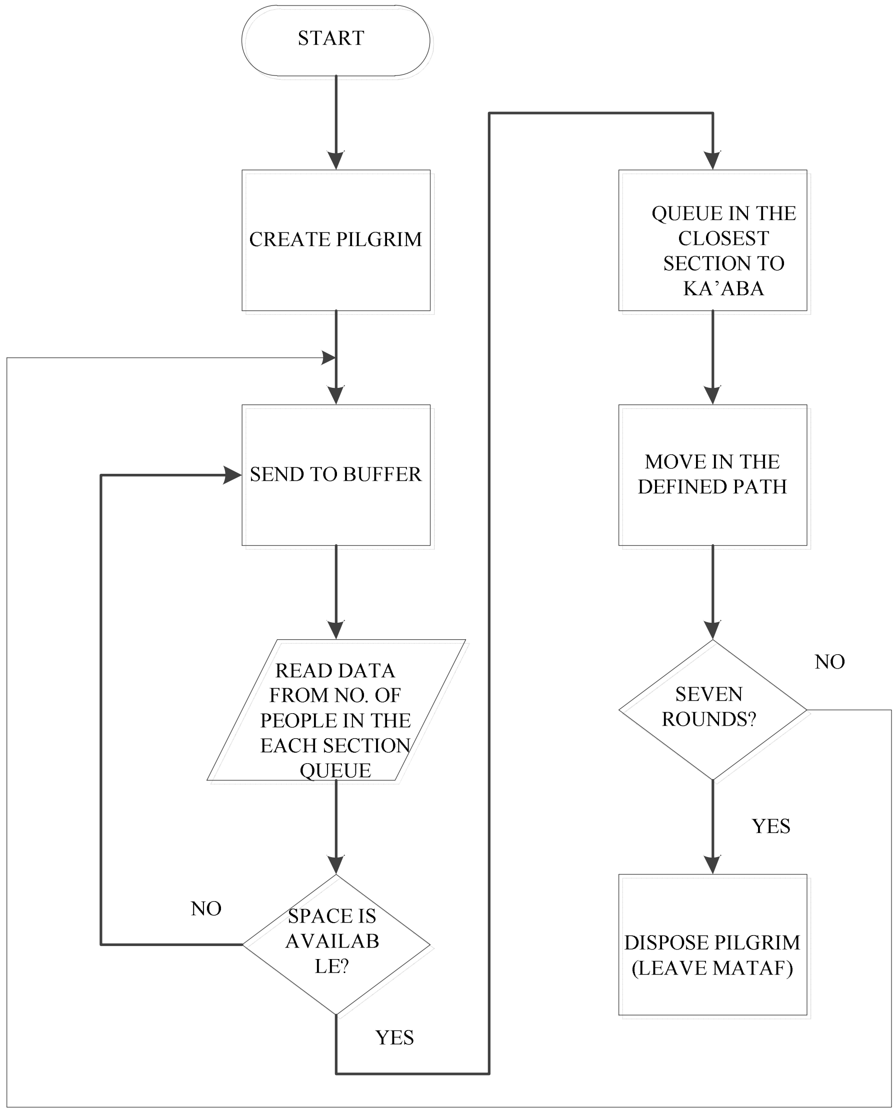

Figure 3: Schematic view of the basic model

4.0 RESULTS

4.1 Screening Experiment

After building the basic model, screening simulation experiment was performed. Critical process factors and direction of adjustment for these factors were determined to further improve the model performance that is to maximize the flow of pilgrims. Series of tests were performed in which purposeful changes were made to the investigated factors to identify corresponding effects to the output response. The objective of the experiments was to determine significant factors to the system's performance (response), specifically, the service rate, average time, and crowd density. In this study service rate refers to the number of people finish *Tawaf* in two hours. Average time refers to the average time a pilgrim performs *Tawaf* in the presence of 2000 person in the *Mataf*. Density refers to the average number of people in each square meter of the *Mataf*.

Choice of factors and levels was based on the published literature. Table 2 shows the factors and levels used in this study.

Table 2: Factors and Levels

Factors	**Levels**	
	Low (-)	**High (+)**
A. Inter-arrival Time (Second)	0.15	3.6
B. Group Size (person)	1	50
C. Space Limitation (%)	0	50
D. Switching between queue lines	Not Allowed (0)	Allowed (100%)

Table 3 summarizes the results of experiments on four controllable factors, namely, Inter-Arrival Time (A), Group Size (B), Space Limitation (C) and the permission to switch between queue lines (D).

A four-factor full factorial experiment with 16 runs and three replications was conducted and the results were analyzed using statistical software, MINITAB. The average value of responses on crowd density, service rate and average time in the system are shown in Table 3.

Table 3: Result of Experiments

RUN	**Std. Order**	**Factors**				**Response**		
		IAT (A)	**Group Size (B)**	**Space Limitation (C)**	**Switching (D)**	**Crowd Density (Pilgrim/ m^2)**	**Service Rate (pilgrim/2 hrs)**	**Average Time in the System (min)**
1	(1)	-	-	-	-	3.5	29333	30
2	a	+	-	-	-	3.9	25890	27
3	b	-	+	-	-	4.7	39344	29
4	ab	+	+	-	-	4.5	24987	25
5	c	-	-	+	-	3.6	20432	36
6	ac	+	-	+	-	4.4	24654	31
7	bc	-	+	+	-	4.6	25222	33

8	abc	+	+	+	-	6.5	21098	30
9	d	-	-	-	+	4	18222	39
10	ad	+	-	-	+	4	21861	30
11	bd	-	+	-	+	7.6	30765	33
12	abd	+	+	-	+	6.6	25870	27
13	cd	-	-	+	+	6	16987	45
14	acd	+	-	+	+	4.7	12876	33
15	bcd	-	+	+	+	8	23543	39
16	abcd	+	+	+	+	7	9994	30

Results of analysis of variance (ANOVA) for average crowd density, average service rate and average time in the system are shown in Tables 4, 5 and 6 respectively.

Table 4: Analysis of Variance for crowd density

Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**
Main Effects	4	26.3850	26.3850	6.5962	14.96	0.005
A	1	0.0100	0.0100	0.0100	0.02	0.886
B	1	14.8225	14.8225	14.8225	33.61	0.002
C	1	2.2500	2.2500	2.2500	5.10	0.073
D	1	9.3025	9.3025	9.3025	21.09	0.006
2-Way Interactions	6	4.5400	4.5400	0.7567	1.72	0.285
A*B	1	0.0025	0.0025	0.0025	0.01	0.943
A*C	1	0.0900	0.0900	0.0900	0.20	0.670
A*D	1	2.4025	2.4025	2.4025	5.45	0.067
B*C	1	0.0225	0.0225	0.0225	0.05	0.830
B*D	1	1.9600	1.9600	1.9600	4.44	0.089
C*D	1	0.0625	0.0625	0.0625	0.14	0.722
Residual Error	5	2.2050	2.2050	0.4410		
Total	15	33.1300				

Two of the main effects were significant at $\alpha = 0.05$ and affected the density. Significant factors are Group Size (B) and switching between queuing lines (D), which had significant effect on the crowd density. Two-way interactions were not significant. The above results suggest that the most important factor in crowd density development is the pilgrim group size (B), followed the degree of switching between queuing lines (D).

Table 5: Analysis of Variance for Service Rate

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	4	539891167	539891167	134972792	8.86	0.017
A	1	83804870	83804870	83804870	5.50	0.066
B	1	58400164	58400164	58400164	3.84	0.108
C	1	236129322	236129322	236129322	15.51	0.011
D	1	161556810	161556810	161556810	10.61	0.023
2-Way Interactions	6	121562220	121562220	20260370	1.33	0.386
A*B	1	86638864	86638864	86638864	5.69	0.063
A*C	1	139502	139502	139502	0.01	0.927
A*D	1	92112	92112	92112	0.01	0.941
B*C	1	26915344	26915344	26915344	1.77	0.241
B*D	1	6105841	6105841	6105841	0.40	0.554
C*D	1	1670556	1670556	1670556	0.11	0.754
Residual Error	5	76134365	76134365	15226873		
Total	15	737587752				

The results indicate that space limitation (C) and switching between queuing lines (D), were significantly affected the hourly service rate. That is by increase any of these factors, the service rate decreases and vice versa. All two-way interaction between the above factors were not significant at α= 0.05.

Table 6: Analysis of Variance for average time in the system

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	4	363.750	363.750	90.938	105.43	0.000
A	1	162.563	162.563	162.563	188.48	0.000
B	1	39.062	39.062	39.062	45.29	0.001
C	1	85.563	85.563	85.563	99.20	0.000
D	1	76.563	76.563	76.563	88.77	0.000
2-Way Interactions	6	41.375	41.375	6.896	8.00	0.019
A*B	1	3.063	3.062	3.062	3.55	0.118
A*C	1	3.062	3.063	3.063	3.55	0.118
A*D	1	27.562	27.562	27.562	31.96	0.002
B*C	1	0.062	0.062	0.062	0.07	0.799
B*D	1	7.562	7.562	7.562	8.77	0.031
C*D	1	0.063	0.063	0.063	0.07	0.799
Residual Error	5	4.312	4.312	0.862		
Total	15	409.438				

The results in Table 6 indicate that all the factors were significant and affected the average time in the system. While switching between queuing lines (D), and Space Limitation (C) had direct effect on the average time in the system, that is by increase of each of these factors, the average time in the system increases and vice versa. However, as the number of people in each group (B) and inter-arrival time (A) increases, the average time in system, decreases. This results suggest that factor B and A has indirect relationship with the average time in the system. Furthermore, the interaction between Inter-Arrival Time (A) and Switching (D) and also between Group Size (B) and

Switching (D), adversely affected the average time in the system. The most significant factor for this response is inter-arrival time (A).

The objective of this study is to propose improved models which lead to an increase in service rate, decrease crowd density and reduced time in the system. Therefore, the switching and space limitation should be minimized in the improved model to optimize all the responses. Large group size decrease the average time pilgrims spend in the system, but also increase the density that is not desirable. So, the tradeoff for determining the average group size should be considered. The tradeoff among these factors led to creation of three alternative improved models.

On an open *Mataf*, a maximum throughput is 30,000 pilgrims for a sustainable, stable system in dynamic equilibrium [1]. At high throughput (>30,000 pilgrims/hour) the mataf area becomes unstable, with the high risk of progressive crowd collapse and–mass fatalities. The basic model which reflects the actual system behavior is not safe. An improved model should be introduced to make adjustments in the flow of people and maintain the safety issues in tolerable range. Improved alternative models are designed based on findings from the basic model.

The finding from basic model suggests that restricting and controlling the switching behavior of pilgrims between the lines, sometimes lead to lower density, faster *Tawaf* and higher service rate. Subsequently improved models are introduced that take advantage of controlling switching behavior by designing spiral path and separating the pilgrims with different characteristics. In a classical queuing model, servers are always available. However, in many practical queuing systems such as *Tawaf* queuing system, areas which are defined as servers may become unavailable for a period of time due to a variety of reasons. This period of server absence may represent the areas which are busy with some supplementary jobs such as under maintenance and cleaning. To analyze these scenarios, server vacation in queuing models was introduced to represent the period of temporary server absence. Allowing servers to take vacations make queuing models more realistic and flexible in the study of real-world waiting-line systems [23].

4.2 Alternative Improved Models

Four improved models were investigated. The first two models schedule the admittance and restrict the inflow according to the server vacancy (space limitation) criteria. Models 3 and 4 were designed based on separation and switching criteria.

Model 1 schedules the admittance (incoming) in such a way that the capacity of the *Tawaf* area is not exceeded, Model 2 controls the inflow and effectively maintain the crowd within the capacity of the restricted area, Model 3 has separated route for men, women and wheelchairs and Model 4 presents *Tawaf* in spiral pass around the *Ka'aba*, which encircle it seven rounds.These models are compared according to performance measures shown in Table 7.

Table 7: Comparison of Alternative Models

Response	Models				
	Basic Model	**Model 1**	**Model 2**	**Model 3**	**Model 4**
Density (Pilgrim/m2)	8	5	4.5	6	5.2
Average Time in the System (min)	32.3	20.8	18.2	26	24
Service Rate (Pilgrim/2hrs)	95414	53213	49068	88253	74431

4.3 Model Verification and Validation

Verification is the step to verify if the model is coded correctly. There are two basic approaches to test simulation software which is called static and dynamic testing. Dynamic testing was done to investigate the input-output relationship using different validation technique such as the continuity test, degeneracy test and consistency test. Continuity test was done by increasing the delay time of certain process and analyzing the output, while for the degeneracy test, a process and its machine was removed from the system and the output of that area was evaluated. Consistency test is done by changing the random number streams of the machine to see whether the result is merely the same or not. In ARENA this is done automatically by the software [22].

In the validation test, the simulation model output will be compared to the actual output. Specifically for this study, average time in the system from three replications was compared with the actual value reported in literature [4].

Based on the simulation replication, the average waiting time for the Basic model is 32.3 minutes. On the other hand, the actual waiting time average for three month is 35 minutes [4]. In order to validate the model, the percentage of variation between the actual (benchmark) and the model should not exceed 15% at 5% average error. Since the variation between the Benchmark and the model's performance is only 7.7%, the Basic model is considered valid [25]. Due to lack of published benchmarked values, comparison for other performance measures was not possible.

4.4 Comparison of Alternative Models

Each of the four alternative models, namely, Model 1, Model 2, Model 3 and Model 4 have their own specific features. The tradeoff among these models made the decision making process a challenging task. Different model may be suitable for a different situation such as for peak season during *Hajj* and *Ramadhan*, while different model may be better to represent non-peak periods.

As shown in Figure 4, the Basic Model has the highest density and smallest average time in the system. Even though Basic Model gave the highest service rate in two hours, but such scenario may lead to undesirable and dangerous excessive crowd. There is no compromise when dealing with safety issues. Therefore the Basic Model that represents the current actual system of *Tawaf* is not desirable in any aspect of objectives of this study.

Improved Model 1, restrict the admittance by schedules in such a way that capacity of *Tawaf* area is not exceeded. We can see that the advantage of this model over the basic model is in decreasing the density and average time in the system as well as service rate to maintain it in a marginal safe level.

Improved Model 2, in comparison with all the investigated models has the poorest scores in all performance measures. Its Service Rate is about half of the basic model. Furthermore controlling the inflow may be difficult and impractical during peak season.

Improved Model 3 with separation of men, women and wheelchairs in different routes, could achieve high service rate with low crowd density and lowest average time in the system. It seems that this model is highly effective during peak period. Furthermore, separation can avoid collisions, unwanted free mixing and may help pilgrims to concentrate on *Tawaf* rituals.

Improved Model 4 is based on spiral path model [6]. This model stands in the third rank in all the performance measure criteria. It seems to be suitable for semi-peak to highly peak periods. It gives high service rate while avoiding accidents by channeling the pilgrims through spiral path and preventing pilgrims from switching lanes.

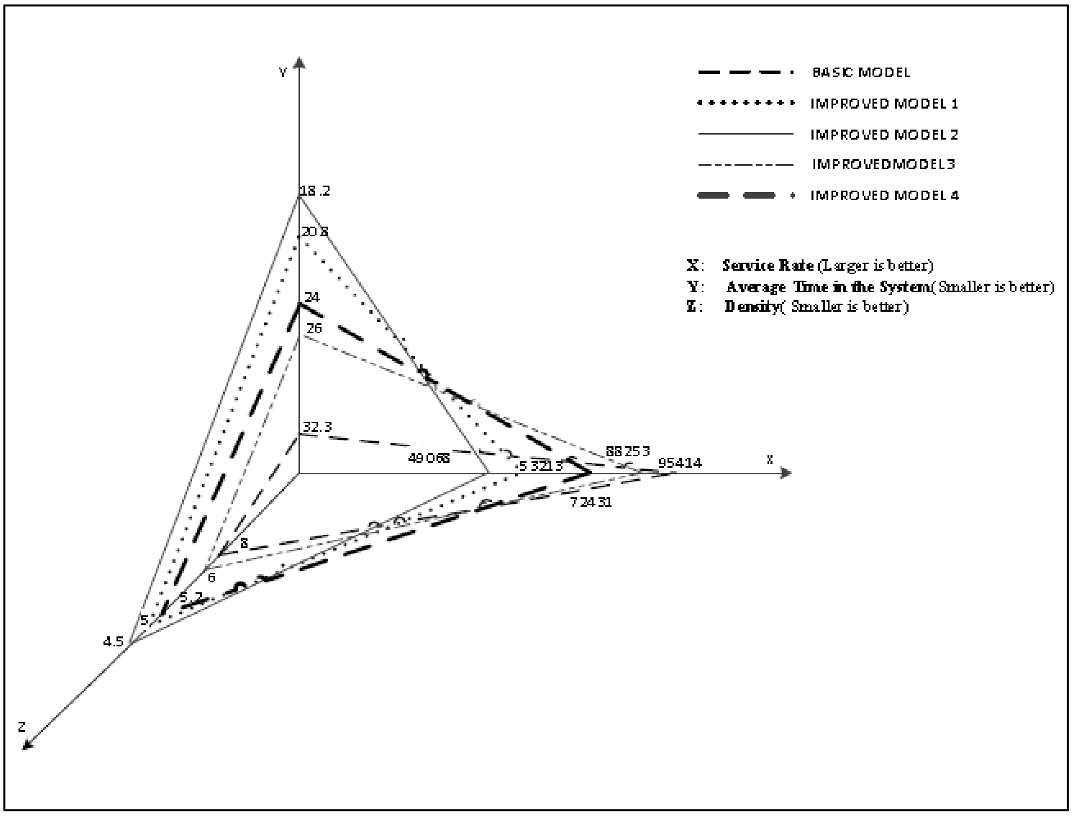

Figure 4: Comparison of Alternative Models

4.4 Comparison with Previous Works

Literature review provides two similar studies that investigated the average time in the system for *Tawaf* and thus can be compared to the results of this study. Other performance measures are not reported in literatures reviewed.

Al-Haboubi and Selim [6] studied spiral path design and mathematical calculations were carried out to estimate the average time in the system. Their results are comparable with the simulation result of the spiral path (Model 4) in this study. Figure 5 shows this comparison.

Zarita *et al*. [4] simulated *Tawaf* Basic and spiral models in SimWalk software using social force method. Figure 6 compares the results from Zarita *et al*. [4] with the current study.

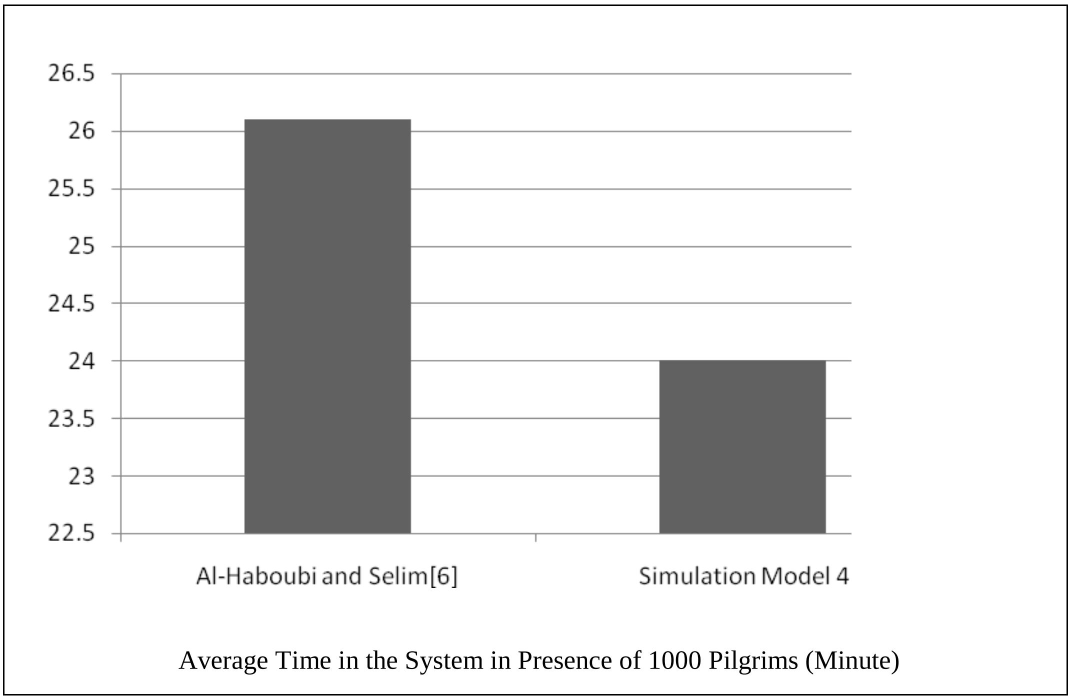

Figure 5: Comparison of Avearage Time in System for Model 4 with Al-Haboubi and Selim[6]

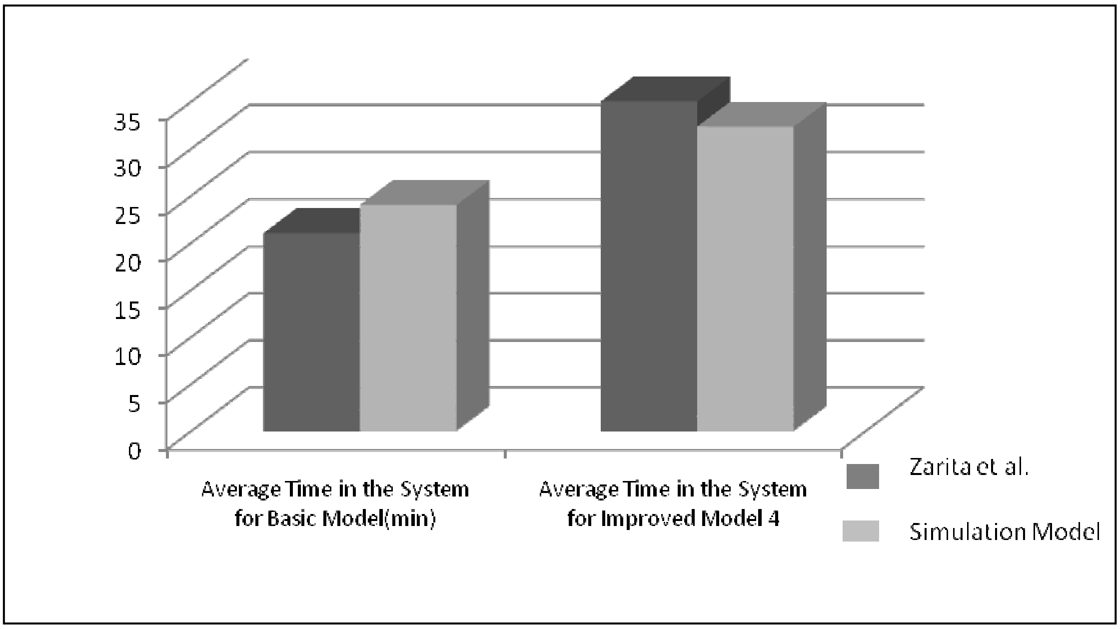

Figure 6: Comparison of Models Performance with Zarita *et al.* [4]

5.0 KEY FINDINGS

Three responses were selected to measure performance of the investigated models. The objective was to find a model that would give high service rate and low crowd density and minimum time in the system. The results of simulation experiments reveal these findings:

i. Switching and Space limitation should be minimized in the improved model to optimize all of the responses.
ii. Large group size can increase the service rate and decrease the time in the system, but also increase the density that is not desirable. Therefore, the tradeoff among the factors should be considered in determining the recommended average group size.
iii. Low inter-arrival time has adverse effect on density and average time in the system; however, it contributes towards increase the service rate.

There is no compromise when dealing with safety issues, therefore, Basic Model that represents the current actual system of *Tawaf* is not desirable in any aspect of objectives of this study.

The Basic Model was enhanced into four improved alternative models. Key findings for the improved models are as the following:

- Improved Model 1 restricts the admittance by schedules in such a way that capacity of *Tawaf* cannot be exceeded. The advantage of this model over the basic model is in decreasing the density and average time in the system as well as service rate to maintain it in a marginal safe value.
- Improved Model 2, in comparison with all the other models has the minimum value in all performance measures. Service Rate is reduced to about half of the basic model. Furthermore, controlling the inflow may not be suitable and practical in peak period.
- Improved Model 3 with separation of men, women and wheelchairs in different routes could achieve high service rate with low crowd density and average time in the system. It seems that this model is highly effective for peak period with high demand and time limitation. Furthermore, separation can decrease collisions and help pilgrims to perform *Tawaf* easier.
- Improved Model 4 or spiral model stands in third rank in all the performance measure criteria. The model looks promising for semi-peak to highly peak periods with contribution towards increase the service rate over the safety range, while the spiral path avoids accidents and prevents pilgrims from switching.

6.0 CONCLUSION

Flow rate determines how quickly the system reaches its dynamic equilibrium. Too high a flow rate makes crowd density builds up too quickly which may cause pilgrims in the *Tawaf* area experience congestion and cannot complete the ritual. If ingress flow continues, this will increase the risk of people crushing and stampede.

According to [1] crowd density above four people per square meter (for moving crowds) is defined as the upper safe limit for crowd flow. At eight people per square meter, the risk to the crowd is defined as intolerable. Scheduling the admittance and dividing the *Tawaf* into different routes has a significant effect on controlling the density and avoiding congestion development, thus creating better *Tawaf* experience for the pilgrims. The simulation results suggested that switching lane during *Tawaf* is the most significant factor in crowd density development and efficiency of the queue system. The alternative model using separation, spiral path and timely scheduled the incoming pilgrim result in the best performance.

Future researches may address different aspects of *Tawaf* such as different queuing rules, group behaviors, and other possible *mataf* designs. The approach of this study is potentially applicable to study other mass crowd movement such as in theme parks, public transportation hubs and sports events.

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