OPTIMIZATION OF HIGH-CROWD-DENSITY FACILITIES BASED ON DISCRETE EVENT SIMULATION

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ABSTARCT

Crowd modelling and simulation has been utilized over the last few decades to study crowd behaviour, estimate evacuation time, and assess safety requirements. In this study, the flow of people in and out of public utilities (washrooms) of a highly populated mosque is simulated. A typical washroom consists of four underground levels located outside the mosque building and can be accessed using staircases or escalators. To study the effect of crowd flow in and out of the washroom during peak times, a new model is built according to the access characteristics to each level. The model is based on Discrete Event Simulation (DES) approach. DES provides the crowd flow behaviour and optimization is performed based on the simulation to obtain the optimized washroom facility to serve the population. The simulation results shows that during peak times when the number of people visiting Haram could reach one-million; the washroom units of the Haram could serve up to about 11.6% of this population. However, the optimization results, given the current washroom layouts, show that if the number of toilets and ablution places are increased by a factor 1.2 the total number of people served would increase to 12.35%. This result is used to make some recommendations which can be further implemented for better layout arrangements, evacuation planning during emergency and public awareness on safety aspects.

Keywords*: *Crowd modelling and simulation, discrete event simulation, evacuation time.

1.0 INTRODUCTION

Crowd simulation is the process of simulating the movement of a large number of people. Currently, crowd simulation is used for modelling the flow of pedestrians during evacuation from a building on fire [1], urban modelling of town planning [2][3], gaming software to enhance the realistic simulation of pedestrians [4], as well as many other applications. In this work, a typical washroom unit of a highly populated mosque is used as a case study for our crowd simulation. The mosque is called Al-Masjid An-Nabawi (Haram) located in Al-Madinah Al-Munawarah, Saudi Arabia. The washroom units of Haram contain both toilets and ablution areas.

The number of visitors to Haram during pilgrimage season has noticeably increased in recent years. During such season, the number of worshipers which include local people and visitors exceeds the million. Pilgrimage season lasts almost 5 to 6 months during the year (from the month of Sha'ban to the month of Muharam in the lunar calendar). Haram becomes extremely populated during the five daily prayers and during the Friday congregation. A number of people require using washrooms before prayer. As the washroom units have limited space, the washrooms become massively populated at this time. Moreover, the traffic in the washroom units is bi-directional in nature and gets very crowded during peak times when people go in and out. We call this duration as peak time. Some reasons we require to manage the crowd include:

- Dangerous and unexpected situations may arise for large crowds especially when dealing with people with different cultures and languages, which is the case of Haram during pilgrimage seasons.

- Large crowds slow or stall the emergency response and communication.
- Unexpected situations such as death may be caused by pushing or panicking during emergency situations.

This work is motivated by observing the scenario of a large number of people using washrooms before a prayer time and perceiving whether the problem can be solved using scientific techniques. Our approach was the idea of a multi-queue model which can be solved by Discrete Event Simulation (DES). To conduct this research work, Haram Authority provides the layouts of washroom units and approves the surveys on the inflow of the people entering washroom.

Our DES provides the flow of people in and out of the washroom units. The washroom units of the mosque have four underground levels below the surrounding open area of the mosque plaza in all cardinal directions. All four levels of washroom units can be accessed by staircases and two of these levels are also accessed by escalators. In the proposed model, the current entering/existing arrangements and the flow of people from all the four different levels of each washroom unit were considered in computing the estimated capacity during peak times. In addition, Our DES provides the nature of flow of the people in and out of the washroom units. Then, optimization is performed based on DES to obtain the optimized size of washroom facility to serve the large population. Since the current washroom layouts can be expanded horizontally (not vertically); the required number of toilets and washrooms are computed in order to achieve an optimized layout. The results can be used to investigate the safety aspects of the nature of exits/entrances and to provide recommendations for better layout arrangements.

This paper is organized as follows: Section 2.0 gives a brief literature survey. Section 3.0 presents the system description. Section 4.0 explains the methodology carried out in this study. Section 5.0 discusses the results and observations of the simulations and finally the conclusion in section 6.0 provides some important recommendations.

2.0 PREVIOUS CROWD SIMULATION RESEARCH WORK

A lot of research has focused on the crowd of people at social gatherings, assemblies, protests, concerts, sporting events and religious ceremonies [5].

From reviewing the literature, it was found that crowds have been simulated using three different approaches namely, fluids, cellular automata and particles. Most of the work in the area of crowd simulation uses the particle approach. The work of Bouvier et al., [6], has applied it to the problem of pedestrian simulation and airbag deployment. The work of Reynolds et al., [7], has simulated crowds of animals, such as flocks of birds and schools of fish where the navigation of each particle was implemented individually according to its perception of the environment, the simulated laws of physics and a simple set of behavioural patterns. The work of Helbing et al. [1], produced a social force model, which uses acceleration, repulsion and attraction forces combined with an additional term to allow for fluctuations in behaviour where it was applied to the simulation of building escape panic. Later Braun et al. modified the work of Helbing et al., by incorporating the concept of a group of pedestrians to the social force model [8]. The work of Thalmann et al., modelled virtual humans according to perception, emotion and behaviour [9]. Probabilistic modelling of pedestrians, which is similar to finite state machines and is based on decision-making and movement [10], has been used by Sung et al. where particles are allowed to move from one state to the next. Other work based on decision-making and movement includes the work of Musse et al., [11] and Loscos et al. [12].

The work by Narain et al. [13] presented a scalable approach for simulating large crowds, using a dual representation both as discrete agents and as a single continuous system. This work has resulted in a hybrid representation for large crowds with discrete agents using Lagrangian and Eulerian methods, a new continuum projection method that enforces density dependent incompressibility to model the varying behaviour of human crowds, and a scalable crowd simulation that can model hundreds of thousands of agents at interactive rates on current desktops.

DES have been used in crowd simulation, for example, the work of Qiu and Hu, [14] presented a discrete event approach for simulating non-uniform pedestrian movements to exploit the crowd system's spatial-temporal heterogeneity. Their experimental results show that the DES approach is faster and more efficient for uniform crowd than discrete Time Simulations. The author in [15] proposed a crowd simulation framework based on DES and cellular automata models to simulate the circular Tawaf movements around the Kaabah in Masjid Al-Harma in Makkah, Saudi Arabia. In [16 – 17] the authors used crowd density information to help characters avoid congested routes that may lead to traffic jams. The technique proposed measures the desirability of a route by combining distance information with crowd density information. A navigation mesh is built for the walkable regions which keep an up-to-date density values. The skeleton of this navigation mesh is the medial axis. Forces are used to guide the characters through the weighted environment created by the density values mapped onto the medial axis to form a weighted graph. The characters periodically re-plan their routes as the density values are updated. The results show that congestion-avoiding paths can be created for thousands of characters in real-time.

A large number of other researches have incorporated social forces [18 - 20], psychological effects [21], and other models of pedestrian behaviour [22 – 24]. Many methods have also been proposed for collision avoidance between nearby particles, these include geometrically-based algorithms [25 - 27], grid-based methods [12][28], and force-based methods [29 – 30][16]. For more information and details on the topic the reader is referred to "Crowd Simulation" book by Thalmann and Musse [31] and the following surveys available in literature: Schreckenberg, et al. [32], Leggett [33], Ryder and Day [34] Thalmann et al. [35], Pelechano et al. [36], Pettr´e et al. [37], and Tasse [38].

Crowd scenario is composed of discrete individuals rather than continuous fluid. Therefore, in this work the crowd of pedestrians entering and exiting the washroom units of the Haram will be modelled using the particle approach with DES where each pedestrian is considered as an entity by itself. Our objective is to simulate the crowd scenario in the unique structure of the washroom units of Haram, and to optimize the number of toilets and ablution places in each washroom unit. To achieve this objective, a multi-queue model is constructed and DES algorithm is used to compute the flow of people in and out of the washroom units. DES algorithm is completely new as it is used to solve our queue model for such complex unique washroom structure. It considers the actual inflow of people inside each level of washroom unit and the interflow between each level. The queuing system inside each level has a complex pattern due to the many toilets and ablution places. To the best knowledge of the authors, such model or algorithm has not been explored in the literature which deals with such a unique problem with different levels and access characteristics especially the queues (queues in each ablution and toilet places). Moreover, simulating the crowd scenario with other techniques such as cellular automata, social force model etc. would have been very complex due to the complexity of geometry and multi-queue system.

3.0 OVERVIEW OF HARAM PLAZA

The washroom units are located underneath the Haram plaza of the surrounding open area of Haram, and can be accessed from the Haram plaza or the underground parking lots. Fig. 1 shows the approximate locations of the washrooms (x) and car parking areas (P). There are 4 levels containing 4 washroom areas as shown in Fig. 2(a) and 2(b). Two underground parking lots are located at level 2 and 4. Note that all the figures are not given in scale and that figs. 3(a-b) show the layouts of the washroom units. Most of the Washroom units have the layout as shown in Fig. 3(a). Therefore, in this work only the layout in Fig. 3(a) is considered.

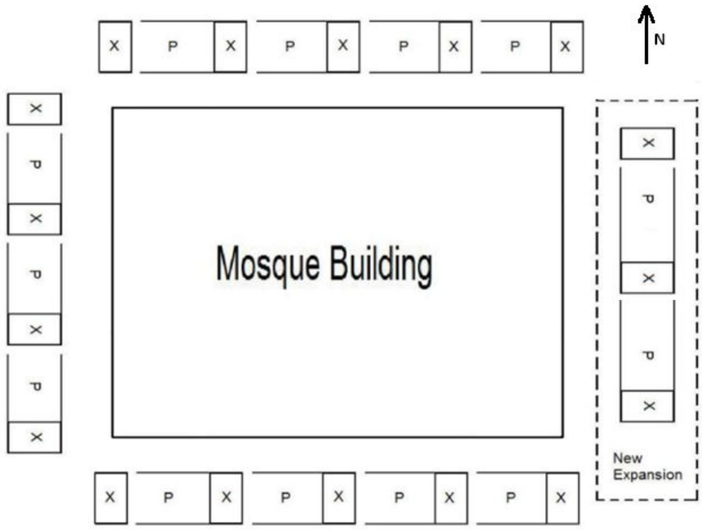
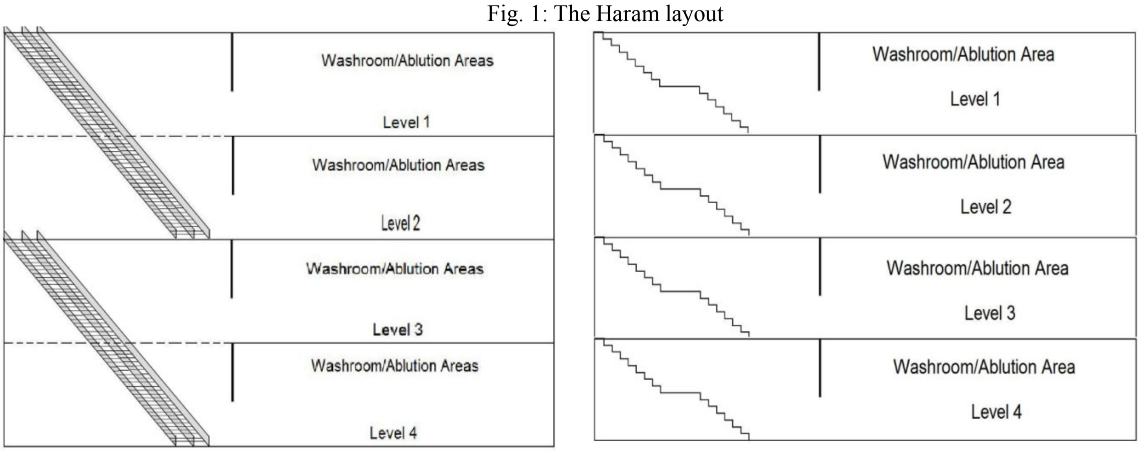


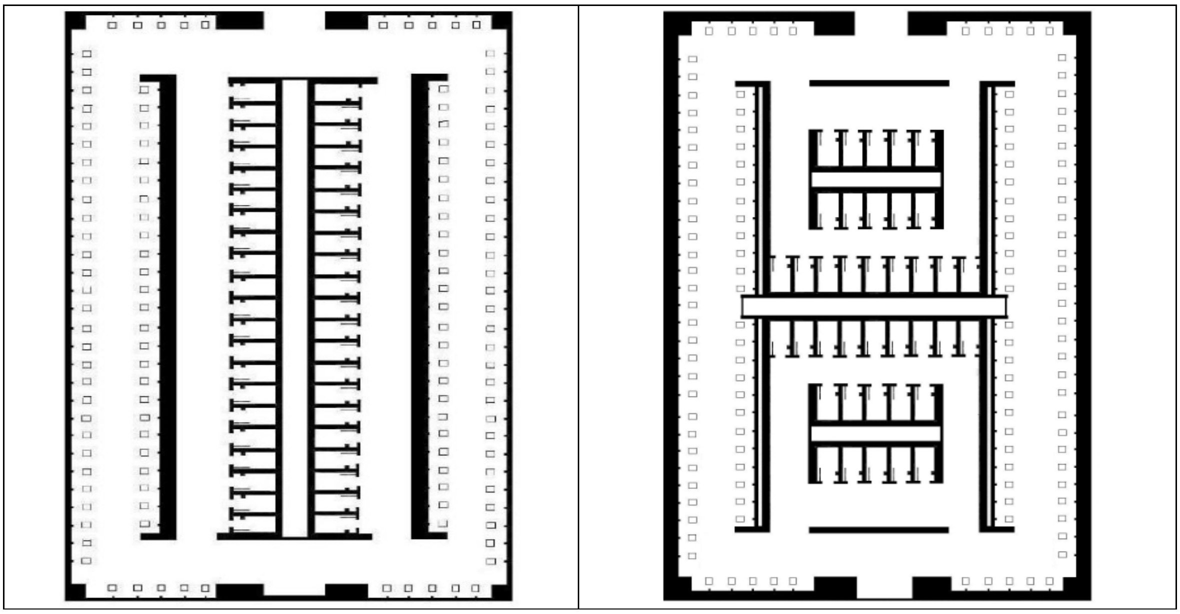
Fig. 1: The Haram layout



(a) (b)

Fig. 2: Cross-Sectional views of the washroom units showing the staircases and escalators

It has been observed that the crowd flow for the washrooms varies due to their locations in reference to main entries of the Haram. The highest crowd flow is noticed at the washroom units near the North or West doors. Moreover, the crowd flow varies in each level of a washroom according to the accessing methods. As demonstrated by Figures 2(a-b), people can access different levels using stairs or escalators. Escalators tend to be more appealing due to the fact that people do not need to exert any effort when using them. However, stairs are preferred when escalators are heavily crowded. Levels 2 and 4 are connected by escalators and stairs from ground level. Levels 1 and 3 are connected by stairs from the ground level. The highest flow of people is observed in level 2 followed by level 1, level 4 and level 3, respectively. Note that level 1 has a higher flow than level 4 as it is closer to the Ground level.



(a) (b)

Fig. 3: Top View of washroom units showing the different layouts

Other entrances to a washroom unit are observed from parking lots at levels 2 and 4. Most of these people entering the unit directly get out of the unit to arrive at the Haram building. Very few people coming from the parking use the washrooms as most of them come from their homes ready for the prayers. When entering the washroom unit people tend to use the toilets closer to the entrances and block the way to those toilets that are away from the entrance. This sometimes gives a false alarm that the capacity has been reached and people sometimes may tend to go to other lower levels to avoid the crowd.

It is noticed that more people wait for toilets than the ablution areas since the number of water taps for ablution is much greater than the number of toilets. Once people are in the washroom unit, they divide into two main categories; those who are using the toilets and, then, the ablution areas, and others who use the ablution areas only. The ratio of how many people use any of these two facilities cannot be explicitly determined. It was noticed that the number of toilet users is smaller during the two evening prayers as people who use the toilets during the first evening prayer most likely would not use it in the following prayer due to the short time lapse between 2 prayer times. The people who use the toilets look for the empty ones or stay in a queue for those with the shortest line. Toilet users take 3-7 minutes in the toilets. People who have used the toilets must use the ablution. Therefore, the people who want to make ablution look for an available seat at the ablution area or stay in a queue with shortest line for ablution. Ablution users require 2-3 minutes to complete their ablution. Then they leave the washrooms using staircases or escalators depending on the level where they are located.

The washroom in Fig. 3(a) is capable of holding 606 persons in each level assuming that an average of 4 people are waiting to use the toilets and 2 people waiting for the ablution areas.

The next section explains the methodology used to model and simulate the crowd entering/leaving the washroom units of the Haram.

4.0 METHODOLOGY

Suppose that the peak time of using washrooms is *T*. This estimation should be based on the fact that people start to use the washrooms before the call for the prayers (Athan) and continue for sometime after Athan. The flow reaches almost maximum when Athan is being made. The flow decreases rapidly when the prayer starts. This event can be modelled using a Gaussian Distribution Function. Fig. 4 shows the model of flow of people entering a washroom level over a period T. Note that a time $t = T/2$, the flow of the people f reaches to maximum value A which is a short time after Azan time $t = T_1$. Note that at Athan time, T_1, most of the people generally go for the washrooms and they require $(T/2 - T_1)$ time to reach the washroom. At $t = T_2$, the prayer starts and f_i decreases rapidly. f_i decreases to almost 0 at $t = T$ when the prayer is completed. This model of the inflow of the people at level i can be built using a Gaussian distribution function as follows.

$$f_i = A_i \exp\left[-c\left(t - \tfrac{T}{2}\right)^2\right] \quad (1)$$

where A: is the maximum flow of people at Athan time entering a level i [no. of people/min].
T: is the estimated duration of peak time [min].
c: is a constant adjusting the width of the curve.
t : is the time [min].

To build the model of the flow behaviour of the people at all the levels of a washroom unit, we need to consider the access characteristics of all levels (see Fig. 2). People entering the washrooms prefer to choose the closest and easily accessed levels, i.e., levels 1 and 2. Level 1 is connected by stairs and is the closest to the ground level. Since level 2 is connected by escalators with the ground level, it is most preferred by people. Level 4 which is connected by escalators with level 2 and connected by stairs with level 3 experiences less crowd-flow than level 1 and 2. Hence, the least crowd-flow occurs at level 3 as it is only connected by stairs with level 2. Therefore, maximum flow characteristics of $A_3<A_4<A_1<A_2$ should be considered for the equation (1).

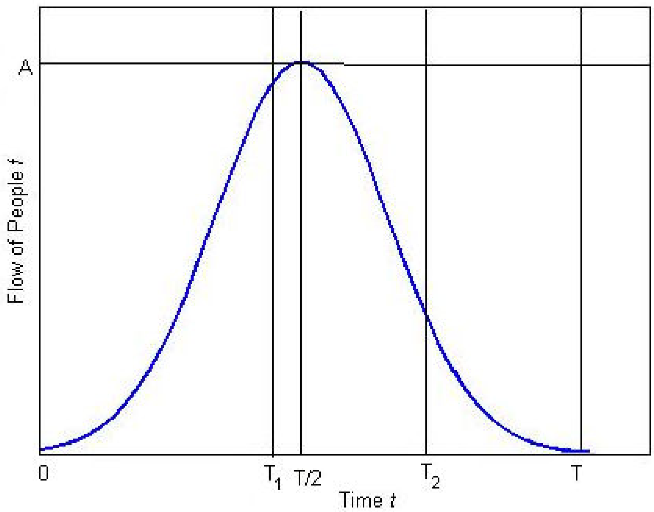


Fig. 4: Inflow of the people to each level over a time period of T modelled by equation (1).

Since we consider a peak time of period T during which people are entering washroom and aim to develop the discrete event model, T is discretized in n uniform grid of time steps {0, h, 2h, ..., nh} with a step size h for a corresponding set of iteration steps {0, 1, ..., n} as shown in Fig. 5.

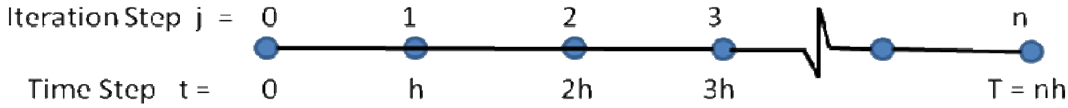


Fig. 5: Uniform grid of time steps for corresponding iteration steps

Suppose that P_i(t) indicates the number of people entering level *i* at time *t*, which is in the small interval [t_1 , t_2]. For discrete event, we consider $t_1 = (j-1)h$, $t_2 = jh$ and $j \in \{0, 1, \cdots, n\}$ is an iteration step. Then, we compute P_i(t), equation (2), by integrating the function in equation (1) over the time interval [t_1 , t_2] as follows.

$$P_i(t) = \int_{t_1}^{t_2} f_i(t)dt = \int_{(j-1)h}^{jh} f_i(t)dt \qquad (2)$$
$$\Rightarrow P_i(jh) \approx f_i(jh)h$$

Note that the integration in equation (2) is approximated by the numerical integration with rectangular method.

Now, we consider that the washroom level has limited capacity which restricts the people to get in the washroom level making the rest of the people queue. People who enter a level to use toilets or to make ablution are chosen randomly. People are assumed to use the nearest available toilet and ablution seat. The subscript *v* is used to denote the toilets and *w* to denote ablution places. We assume that a person requires t_V minutes in toilet and t_W minutes in ablution. Toilet users must use ablution places, where ablution is required before performing prayers. Toilet users will be queued if toilets are occupied. Assume that a maximum of q_V people can stay in the queue for toilets. Similarly, a maximum of q_W people can stand in the queue for ablution. Once the system is full, they start lining up in front of these places and use it in a systematic manner (first come, first in). When all places along with queue are filled, then the remaining people e_i wait to get in the queue. However, a number of people go to the next level to find less crowded areas. Suppose that a fraction $C_{i,k}$ of the remaining people move from level *i* to *k*.
Consequently, the number of people must be updated by adding those who are waiting to get in the queue in the previous step. Assume that it takes the same time *h* of step size to move from a level to the next by using either the staircases or escalators. Then, the number of people entering the level 1 is given by equation (3):

$$P_1(jh) \approx f_1(jh)h + C_{1,2}e_1([j-1]h) \qquad (3)$$

The number of people coming to enter the level *i* = 2 to 3 is given by equation (4):

$$P_i(jh) \approx f_i(jh)h + (1 - C_{i-1,i})\, e_{i-1}(jh) + C_{i,i+1}\, e_i([j-1]h) \qquad (4)$$

The number of people coming to enter the level 4 is given by equation (5):

$$P_4(jh) \approx f_4(jh)h + (1 - C_{3,4})\, e_3(jh) + e_4([j-1]h) \qquad (5)$$

The number of people e_i waiting to get in the queue at time step *jh* can be calculated by equation (6):

$$e_i(jh) \approx \max(0, \quad d_i(jh) - P_{i,\max}), \qquad (6)$$

where

$$d_i(jh) = P_i(jh) - G_i(jh).$$

Algorithm 1: Discrete event algorithm for computing inflow and outflow of the washroom

Input: Step size *h*, number of time steps *n*. $C_{i,i+1}$ for *i* = 1 to 3. f_i requires
c and A_i for *i* = 1 to 4 which is computed using equation (1).

Output: Number of people P_i staying at level *i* at time steps 0, *h*, ..., *nh* for *i* = 1 to 4.

1. Initialization; $e_i(0) := 0$, *for i* = 1 to 4

2. **for *j* = 1 to *n***
   - Calculate P_1 at time step *jh* using equation (3) as
     $$P_1(jh) := f_1(jh)h + C_{1,2}e_1([j-1]h)$$
   - Distribute P_1 to toilet/ablution places randomly. Set the people in the queue of the toilet/ablution places according to the availability. If a person has spent the required time in the toilet/ ablution, the person can get out and is added to $G_1(jh)$.
   - Calculate $e_1(jh)$ using equation (6)
   - Calculate P_2 at time step *jh* using equation (4)
     $$P_2(jh) := f_2(jh)h + (1 - C_{1,2})\, e_1(jh) + C_{2,3}e_2([j-1]h)$$
   - Distribute P_2 to toilet/ablution places randomly. Set the people in the queue of the toilet/ablution places according to the availability. If a person has spent the required time in the toilet/ ablution, the person can get out and is added to $G_2(jh)$.
   - Calculate e_2 using equation (6)
   - Calculate P_3 at time *jh* using equation (4)
     $$P_3(jh) := f_3(jh)h + (1 - C_{2,3})\, e_2(jh) + C_{3,4}e_3([j-1]h)$$
   - Distribute P_3 to toilet/ablution places randomly. Set the people in the queue of the toilet/ablution places according to the availability. If a person has spent the required time in the toilet/ ablution, the person can get out and is added to $G_3(jh)$.
   - Calculate e_3 using equation (6)
   - Estimate P_4 at *jh* using equation (5)
     $$P_4(jh) := f_4(jh)h + (1 - C_{3,4})e_3(jh) + e_4([j-1]h)$$
   - Distribute P_4 to toilet/ablution places randomly. Set the people in the queue of the toilet/ablution places according to the availability. If a person has spent the required time in the toilet/ ablution, the person can get out and is added to $G_4(jh)$.
   - Calculate (e_4) using equation (6)

end (For).

Note that $G_i(jh)$ is the number of people exiting the facility. This is calculated by checking whether a person completes his/her required time in the facility. Suppose that a person wants to use the toilet then he/she will check whether any toilet is free. If there is none available then the person is required to stay in queue until a toilet is available for use; the toilet use requires, t_V minutes. After the use of toilet the person must look for an ablution place. If none is available, he/she must stand in queue. When a seat is available, the person takes t_W minutes to perform ablution then he/she exits the facility.

Now we summarize the above discrete event model in the form of an algorithm in Algorithm 1. This algorithm requires the numerical values of step size *h*, number of time steps, *n*. $C_{i,i+1}$ for *i* = 1 to 3. *c* and A_i for *i* = 1 to 4 are required to compute f_i . This algorithm provides the numbers of people P_i staying at all levels i = 1 to 4 at time steps 0, h, ..., nh. First the queue e_i of the people remaining outside each level i is set to zero. Then for each iteration step the following operations are performed.

The number of people P_i is computed sequentially for all levels i = 1 to 4 using equations (3 - 5). Whether a person uses a toilet or ablution place is determined randomly for all levels i = 1 to 4. The people in the queue of the toilet/ablution places are set according to the availability of the places in the queues which are limited in sizes as q_V, q_W, respectively. If a person has spent the required time in the toilet/ ablution, the person can get out and is added to $G_I(jh)$. Then e_i is updated using equation (6).

Algorithm 1 is used to simulate the flow of people in and out of the washroom areas and the movement of people from different levels. The next section presents the experimental results using the proposed model above.

5.0 SIMULATION RESULTS AND DISCUSSION

The total number of toilets is 42, the total number of ablution places is 132, and the approximate total area of a washroom unit is 693 m^2 capable of holding approximately 606 people at peak time. The following values/assumptions are used for our simulation: The peak time of using washrooms is considered as T = 45 minutes. Athan begins at T_1 = 20 minutes and the prayer starts at T_2 = 30 minutes and ends at T = 45 minutes. Duration of Athan is assumed as 5 minutes. The step size h = 1 minute. Hence, the number of steps n = 45. The time to move from a level to the next level is 1 minute using either the stairs or the escalators.

The flow of people in the washroom unit was modelled using the Gauss distribution function given in equation (1), where the maximum number A_i of people arriving per minute and the constant c were obtained by surveys. c is taken as 0.01, The values of A_i for the four levels were found as follows:

$$A_1 = 160,\ A_2 = 180,\ A_3 = 100,\ A_4 = 70;$$

A person requires t_V = 5 minutes in toilet and t_W = 2 minutes in ablution. The size of the queue for toilet q_V = 4, and for ablution q_W = 2. The fraction $C_{i,k}$ of the remaining people moving from level i to k is taken as

$$C_{1,2} = C_{2,3} = C_{3,4} = 0.5;$$

Fig. 6, plots the number of people during peak time. The graphs in Fig. 6 show that the flow of people grows to the maximum at time $T/2$ = 22.5 minutes which is few minutes after starting time T_1 = 20 minutes for Athan. The flow starts to decrease rapidly at T_2 = 30 minutes when the prayer starts. The flow decreases almost to 0 at T = 45 minutes when the prayer is completed. Using Algorithm 1, the graphs in Fig. 7 were obtained. The results show the maximum capacity of each level is 606 persons. Notice that the number of people is increased until the maximum capacity is reached and the number of people in the level remains constant even if the flow of people increases. When the flow starts to decrease the number of people starts decreasing with some delay (Levels 3 and 4). This delay is due to the waiting time at the level. The figure also shows that the number of people is increasing in level 4 as they assume that lower levels are less populated than the upper levels.

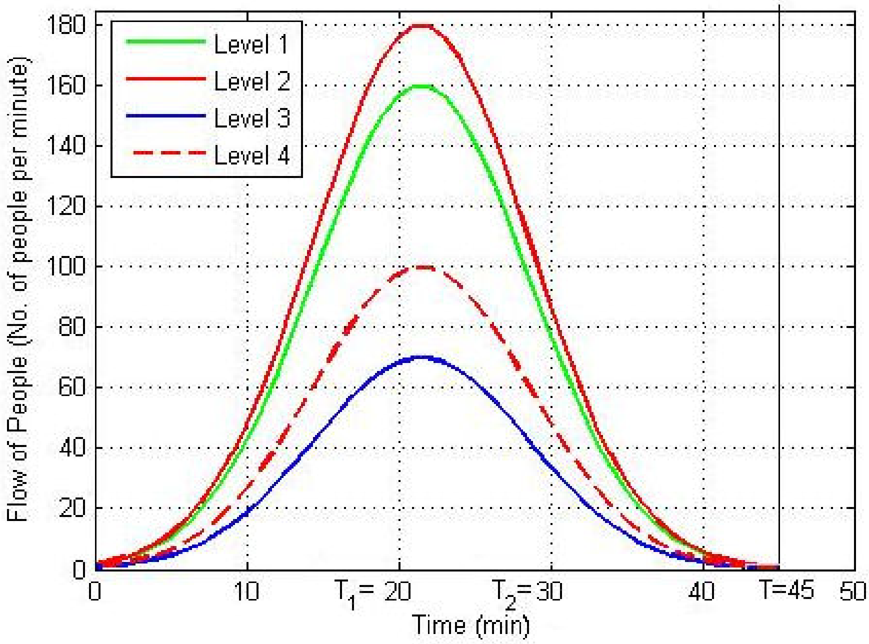


Fig. 6: Flow of the people Vs. Time for each level.

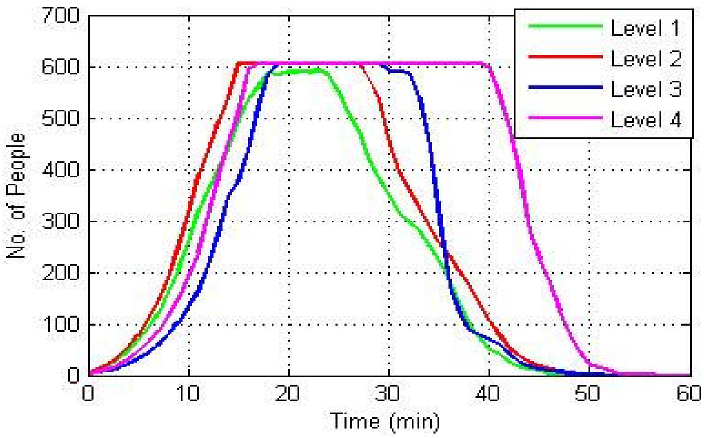


Fig. 7: Number of People Vs. Time for each level

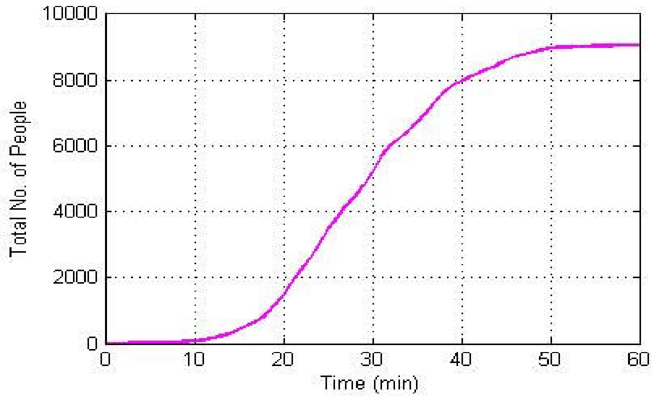


Fig. 8: Total Number of People Vs. Time for 4-levels

Fig. 8 provides the total number of people served using all 4 levels. At time T = 45, the total number of people served is 8340. If the same capacity is allowed for all 14 units around the mosque, assuming all are in service, then the total capacity of the current number of units is 116760. This means that at peak times when the number of visitors is about a million, 11.6 % of the visitors are served during the peak time of 45 minutes. However, the new 3 washroom units which were under construction will provide an increase in capacity of 25,020 people, if the same capacity as other units is assumed; thus, raising the number of people to be served to 14.17 %. The maximum serving capacity seems to be realistic and acceptable.

It is not possible to extend the washrooms vertically to get more levels due to civil engineering constraints. However, it is possible to expand horizontally to obtain more toilets and washrooms in each level. Therefore, we use the same input of Fig. 6 and performed numerical tests to understand the effect of change of the number of toilets and ablutions by some factors. The test results are given in Figs. 9 – 14. In part (a) of these figures, the total number of people residing in each level over the time period is plotted. In part (b), the total number of people residing in all levels over the time period is shown. It is mentioned that the existing system contains 42 toilets and 132 ablution places. In these figures, the number of toilets and ablution places are changed by factors 0.5 to 1.8. For example, 42x0.5=21 toilets and 132x0.5=66 ablution places were considered in Fig. 9. Observe that if the capacity reduces, the less number of people are served in the period of 45 minutes with an increase of waiting time and the levels are full for more period of time. The levels 3 and 4 are fully occupied for longer time as the people's tendency is to find places in the lower levels if the current ones seem to be crowded. If the capacity increases, more people are served in 45 minutes and the plots in part (a) show full occupation for shorter period. However, after a certain increase in capacity, the total number of people served in 45 minutes will not increase.

The prayer starts at T_2 = 30 minute which is a crucial time for the people to join the prayer. At T = 45 minute, the prayer is completed. Figs. 15-16 show the total number of people served with different capacity in the period of 30 to 45 minutes. From these figures, it is apparent that the number of people served is almost constant after certain capacity which is optimum for serving the maximum number of people. Table 1 presents the numerical values from these figures listing the maximum number of people served and optimal capacity in the period of 30 to 45 minutes. Column 1 and 2 provide the time in minutes and the maximum number people served within that time. Column 3 of this table gives the multiplication factors for existing capacity is to obtain the optimal capacity. This result is required for future design of washrooms.

From Table 1, we observe that the maximum number of people served in 45 minutes is 8823 using 14 washroom units the total number of people served is 123,522 which means 12.35% of people at peak time are served. Finally, when the three new units are added 26,469 more people will be served providing a total of 15% people at peak time are served with the optimal numbers of toilets and ablution places as calculated above.

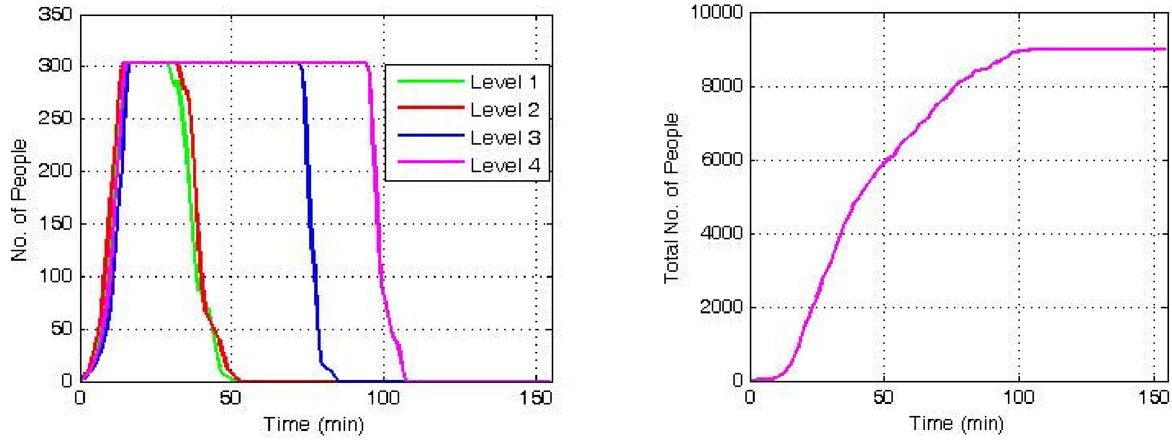


Fig. 9: Total Number of People (a) at each level (b) in all levels over Time with 0.5 times the toilet and ablution places

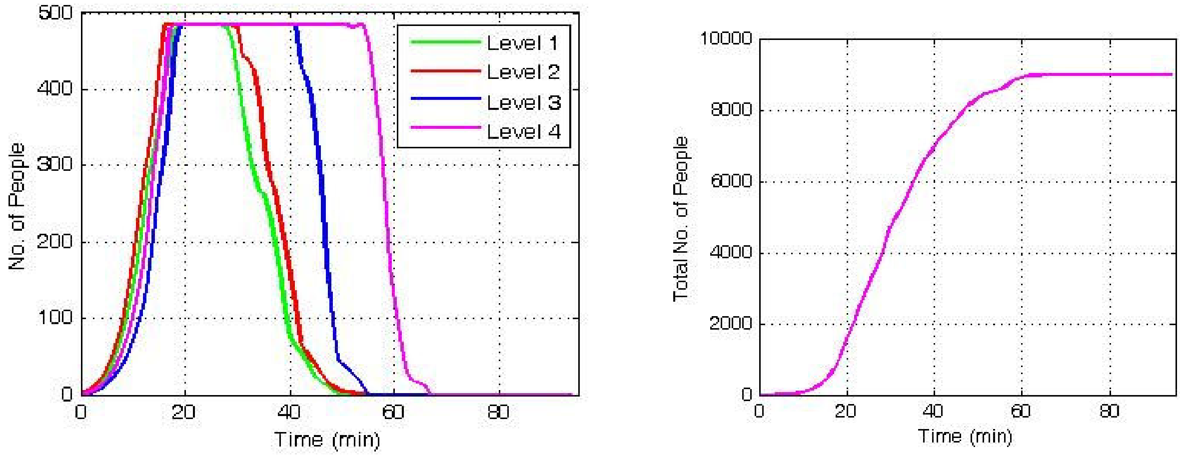


Fig. 10: Total Number of People (a) at each level (b) in all levels over Time with 0.8 times toilet and ablution places

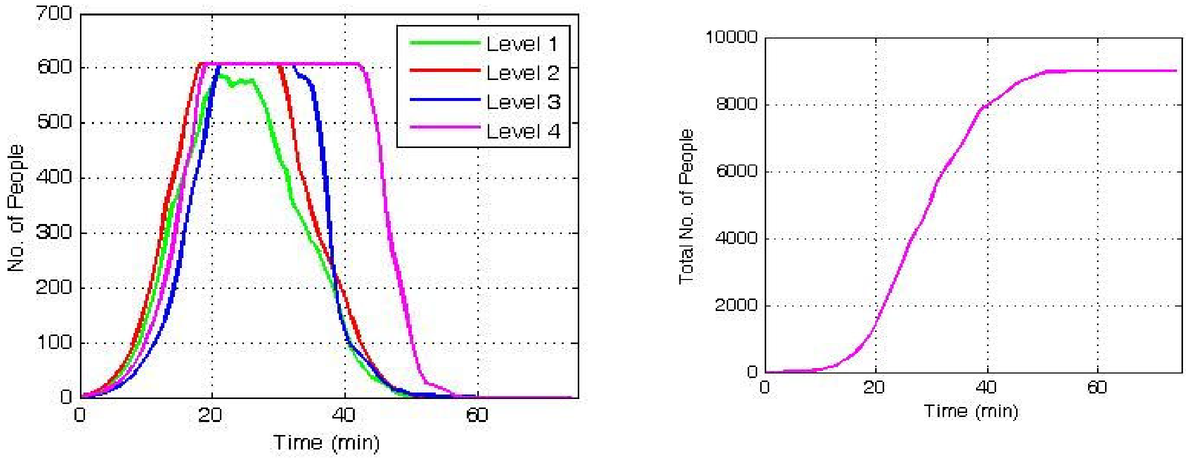


Fig. 11: Total Number of People (a) at each level (b) in all levels over Time with existing toilet and ablution places

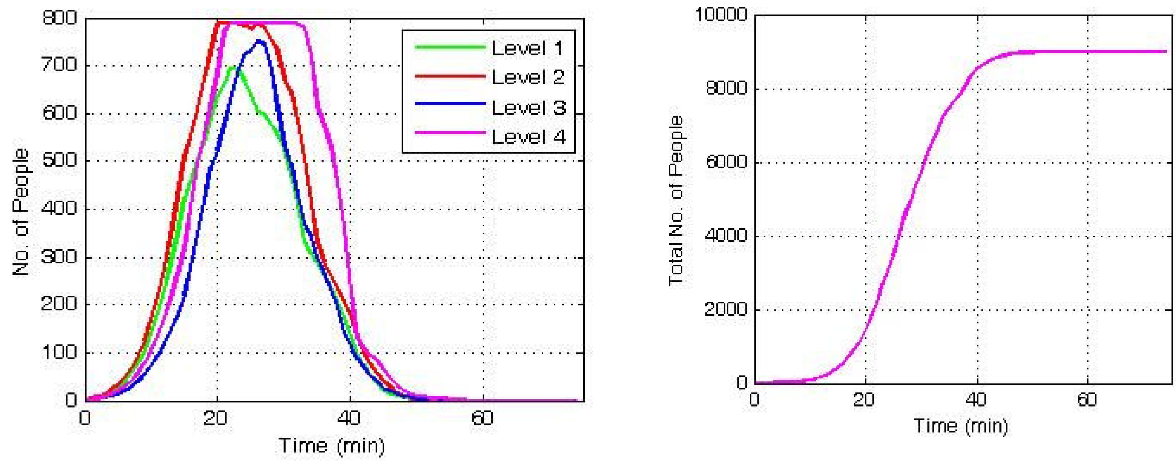


Fig. 12: Total Number of People (a) at each level (b) in all levels over Time with 1.3 times the toilet and ablution places

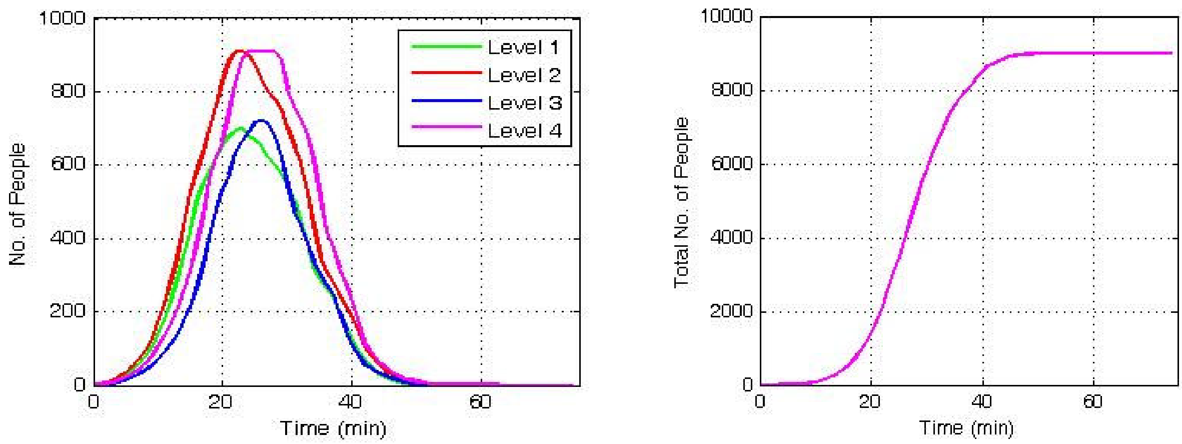


Fig. 13: Total Number of People (a) at each level (b) in all levels over Time with 1.5 times the toilet and ablution places

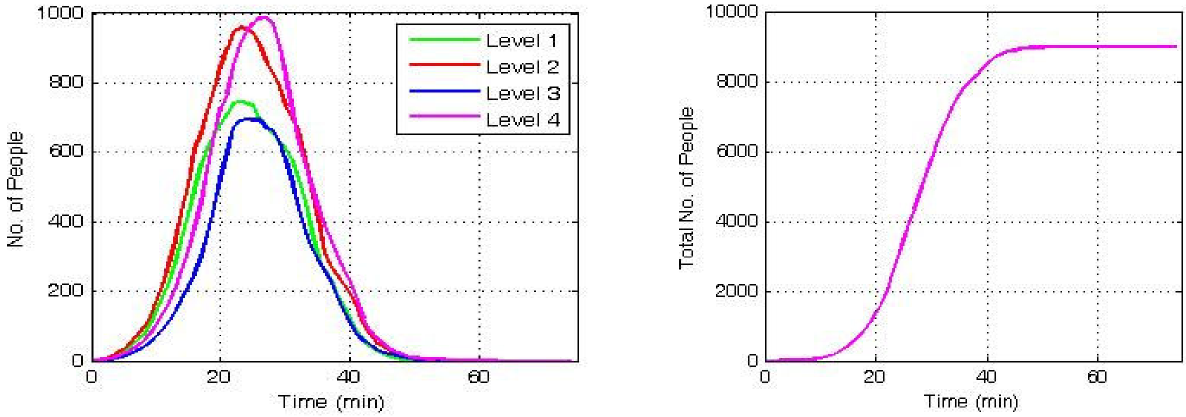


Fig. 14: Total Number of People (a) at each level (b) in all levels over Time with 1.8 times the toilet and ablution places

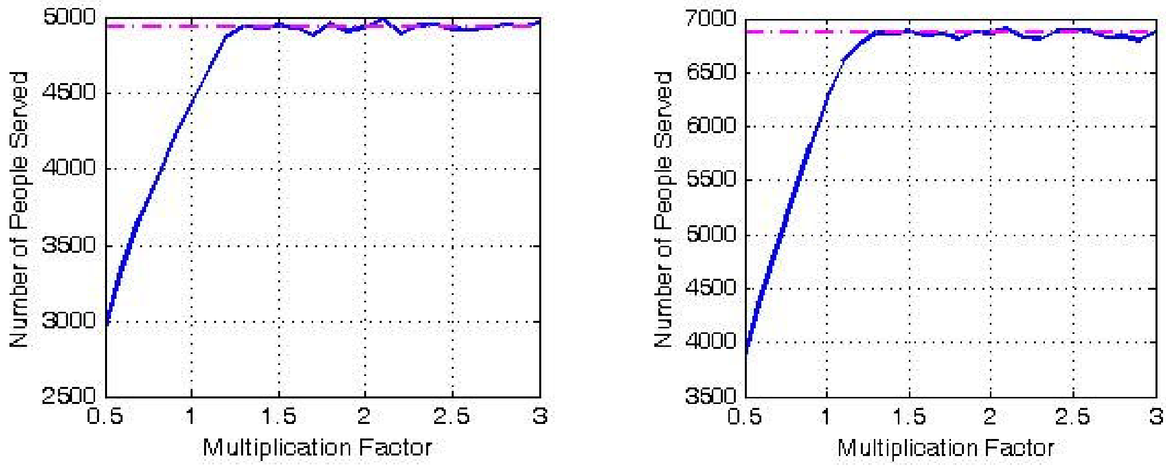


Fig. 15: Total Number of People Served with change in existing capacity with different multiplication factors in the period of (a) 30 minutes (b) in 35 minutes.

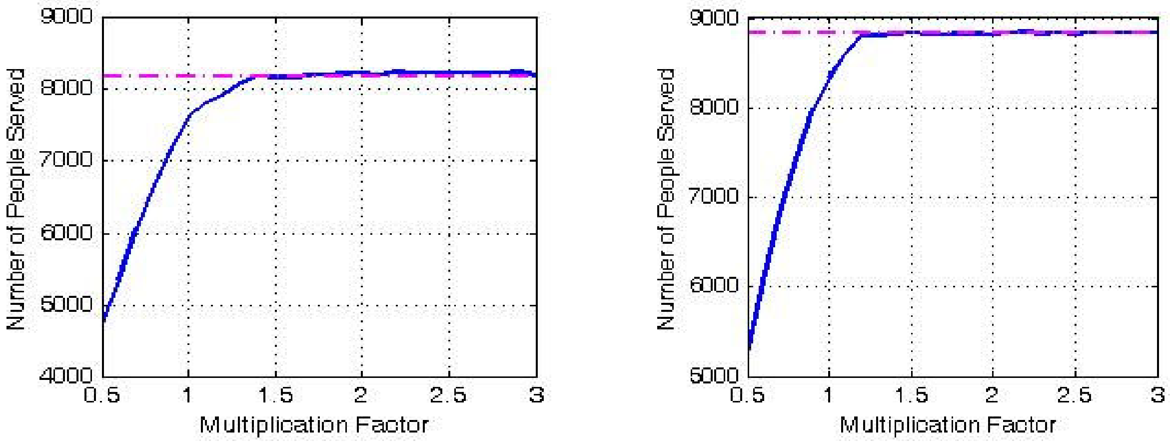


Fig. 16: Total Number of People Served with change in existing capacity with different multiplication factors in the period of (a) 40 minutes (b) in 45 minutes

Table 1: Maximum number of people served and optimal capacity at different time periods

Time (Minutes)	Maximum number of people served	Multiplication factors for existing capacity to obtain Optimum capacity
30	4953	1.3
35	6859	1.3
40	8174	1.3
45	8823	1.2

6.0 RECOMMENDATIONS AND CONCLUSION

We have simulated the flow of the people in and out of the washroom unit of Haram. A discrete event model was built to simulate the flow. This simulation provides the nature of flow of the people in and out of the washroom units during peak times. We obtained that the maximum number of people which can be served by the current layout of washrooms is 8340 during the peak time of a period of 45 minutes. It was noticed that the lower levels become full for a longer period could impose hazardous situations and jeopardize safety. Therefore, it is essential to provide signage to warn and to direct people away from overcrowded levels. To serve the huge population, optimized washroom facility has been determined using optimization based on the simulation. The results of optimization concludes that a maximum of 8823 persons can be served by a washroom unit within 45 minutes, if the current numbers of toilets and ablution places are increased by a factor of 1.2. The results can be used to investigate more on evacuation plans to guarantee the safety of the crowd and to provide recommendations for better layout arrangements. Haram is a unique case study due to the multicultural and diversity of people visiting it. Further study of crowd can be performed to establish standard data, such as speed of pedestrians, size of people, body weight, height of people, size of staircases and other standards related to construction of buildings and include these parameters in the model to achieve more realistic results.

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