Simulation of the Pedestrian Flow in the Tawaf Area Using the Social Force Model

Zarita Zainuddin, Kumatha Thinakaran and Mohammed Shuaib

Abstract**—**In today's modern world, the number of vehicles is increasing on the road. This causes more people to choose walking instead of traveling using vehicles. Thus, proper planning of pedestrians' paths is important to ensure the safety of pedestrians in a walking area. Crowd dynamics study the pedestrians' behavior and modeling pedestrians' movement to ensure safety in their walking paths. To date, many models have been designed to ease pedestrians' movement. The Social Force Model is widely used among researchers as it is simpler and provides better simulation results. We will discuss the problem regarding the ritual of circumambulating the Ka'aba (Tawaf) where the entrances to this area are usually congested which worsens during the Hajj season. We will use the computer simulation model SimWalk which is based on the Social Force Model to simulate the movement of pilgrims in the Tawaf area. We will first discuss the effect of uni and bi-directional flows at the gates. We will then restrict certain gates to the area as the entrances only and others as exits only. From the simulations, we will study the effect of the distance of other entrances from the beginning line and their effects on the duration of pilgrims circumambulate Ka'aba. We will distribute the pilgrims at the different entrances evenly so that the congestion at the entrances can be reduced. We would also discuss the various locations and designs of barriers at the exits and its effect on the time taken for the pilgrims to exit the Tawaf area.

Keywords**—**circumambulation, Ka'aba, pedestrian flow, SFM, Tawaf , entrance, exit

I. Introduction

THE need for better pedestrian facilities has increased in this modern world as the world population is increasing. The pedestrian movement has become a popular study among researchers [1, 2, 3, 4, 5, 6]. The Social Force Model (SFM) was proposed by Helbing and Molnar [9] where the equations of the model are based on second order differential equations which can be solved using standard numerical methods. In SFM, the pedestrians act as individuals and are affected by external and internal forces. Internal force is the force within a pedestrian that motivates him to walk towards his destination. External forces are forces exerted by other pedestrians and obstacles that affect the pedestrian's walking path. The Social Force Model is defined as:

$$\frac{dx_i}{dt} = v_i(t)$$

$$\mathrm{f}_i(t) = m_i \frac{\mathrm{d}\mathrm{v}_i(t)}{\mathrm{d}t} = m_i\, \mathrm{a}_i(t)$$

$$= \mathrm{f}_i^0(t) + \sum_{j\neq 1} \mathrm{f}_{ij}(t) + \sum_{w} \mathrm{f}_{iw}(t) + \sum_{a} \mathrm{f}_{ia}(t) + \sum_{g} \mathrm{f}_{ig}(t) + \xi_i(t) \qquad (1)$$

where $\mathrm{f}_i(t)$ is the sum of all the forces acting on the pedestrians

$\mathrm{f}_i^0(t)$ is the force in the direction of the pedestrians' next immediate target

$\mathrm{f}_{ij}(t)$ is the repulsive force exerted by pedestrian j on pedestrian i.

$\mathrm{f}_{iw}(t)$ is the repulsive force between a pedestrian i and an obstacle

$\mathrm{f}_{ia}(t)$ and $\mathrm{f}_{ig}(t)$ represent the attraction forces that attract pedestrian i toward the alternative source a or a group of pedestrians g in a particular area

$\xi_i(t)$ is a noise term.

Without loss of generality, attraction forces can be omitted from the equation.

This results in the reduced SFM as follows:

$$\mathrm{f}_i(t) = \mathrm{f}_i^0(t) + \sum_{j\neq 1} \mathrm{f}_{ij}(t) + \sum_{w} \mathrm{f}_{iw}(t) + \xi_i(t)$$

$$= m_i \frac{v_i^0}{\tau_i}\left(\frac{\mathrm{r}_i^k - \mathrm{r}_i(t)}{\left\|\mathrm{r}_i^k - \mathrm{r}_i(t)\right\|}\right) - \frac{v_i(t)}{\tau_i} + \sum_{j\neq 1}\left(\frac{A_i}{B_i}\exp\left[-\frac{\left\|\mathrm{r}_i(t) - \mathrm{r}_j(t)\right\|}{B_i}\right]\frac{\mathrm{r}_{ij}(t)}{\left\|\mathrm{r}_{ij}(t)\right\|}\right)$$

$$+ \sum_{w}\left(\frac{A_w}{B_w}\exp\left[-\frac{\left\|\tilde{\mathrm{r}}_{iw}(t)\right\|}{B_w}\right]\frac{\mathrm{r}_{iw}(t)}{\left\|\tilde{\mathrm{r}}_{iw}(t)\right\|}\right) + \xi_i(t) \qquad (2)$$

where

v_i^0 is the desired speed of pedestrian i

$\left(\frac{\mathrm{r}_i^k - \mathrm{r}_i(t)}{\left\|\mathrm{r}_i^k - \mathrm{r}_i(t)\right\|}\right)$ is the unit vector directing to next intermediate target k at time t.

τ_i is the relaxation time (time needed to accelerate from current speed to desired speed.)

$v_i(t)$ is the velocity of pedestrian i at time t ,

A_i is the interaction intensity which is the impact of external forces on the pedestrian. A_i is denoted as the Object Pressure Factor

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B_i is interaction distance, which is the impact of distance between pedestrians on potential exerted by pedestrian *i* to pedestrian *j* and is denoted as Pedestrian Pressure Factor.

Particularly, SimWalk is a computer simulation software which simulates pedestrians' movement. This software is built based on the SFM model and the shortest-path algorithm. It allows users to define the density, destination, the range of speed for pedestrians, the level of service (LOS), time step, radius of pedestrian, A_i, which is the interaction intensity and B_i ,which is the interaction distance. SimWalk is useful as this software can produce outputs that are of interest namely density, walking speed of pedestrians, count and flow rates, duration taken by each pedestrian to complete the simulation, the distance traveled, the start time as well as the exit time of the pedestrians. In SimWalk, the pedestrian's route is affected by his destination, speed, interaction with other pedestrians and existence of other pedestrians and obstacles.

A reduced form of SFM in SimWalk has been presented as the following:

The velocity at time $t+\Delta T$ for the reduced SFM is defined as

$$\mathrm{v}_i(t+\Delta T) = v_i^0 \frac{\mathrm{f}_i(t)}{\|\mathrm{f}_i(t)\|} \quad (3)$$

and the final position of pedestrian *i* is

$$\mathrm{r}_i(t+\Delta T) = \mathrm{r}_i(t) + \mathrm{v}_i(t)\Delta T \quad (4)$$

II. The Holy Ritual Of Tawaf

The holy ritual of circumambulating the Ka'aba (Tawaf) is very important for the Muslim Pilgrims who visit Mecca each year. Pilgrims would need to circumambulate the Ka'aba seven times to complete the Tawaf ritual. The area of Tawaf is usually congested and will get worse during Hajj seasons. Pilgrims that come to perform their Tawaf would enter randomly to join the crowd. Those who have completed their ritual would jostle their way out in the high-volume crowd. This is very risky to the pilgrims as highly dense crowd may push into each other and cause panic-escape situations. Stampedes may also occur in the panic situation. There are namely 5 major entrances leading into the Tawaf area: Al-Omra gate, King Fahad gate, King Abdulaziz gate, As-Sa'a gate and Al-Fatah gate. However, pilgrims tend to use the King Abdulaziz entrance the most as the entrance is the closest to the beginning line of the Tawaf ritual. This causes congestion to occur primarily at the King Abdulaziz entrance as pilgrims use the gates both as entrance and exit. This causes bi-directional flow at the gates and cross-paths occur. Previous studies have been done to decrease the casualties caused by stampedes or overcrowded pilgrims during Tawaf. Many designs have been proposed to improve the pilgrims' movement within Tawaf area. Among the studies, is the study by Haboubi[4] which suggests building a spiral path that begins from the entrance of the Tawaf towards the Alhajar Alaswad where a ramp is then proposed to be built towards an underground tunnel that leads to an exit outside the Tawaf area.

A study was done using Simwalk to discuss the effect of Maqam Ibrahim to the ritual of Tawaf.[3] The study shows that Maqam Ibrahim do not affect the pedestrians' speed in the ritual. The study also discusses the need of crowd control and area extension. The paper did not provide much statistical results as there were some difficulties in obtaining statistical results.

A. The uneven distribution of pilgrims at entrances

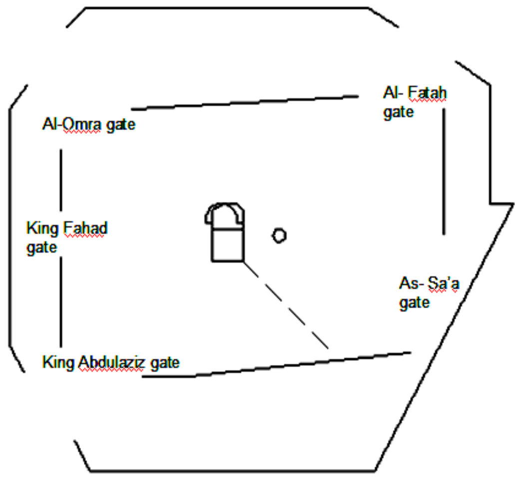


Fig. 1 The entrances into the Tawaf area

As indicated earlier, pilgrims tend to use the King Abdulaziz entrance the most as the entrance is the closest to the beginning line of the Tawaf ritual where pilgrims join in the crowd parallel to the direction of the crowd flow. Thus, less counter flows occur. The maximum use of the King Abdulaziz gate causes congestion to occur the most at the gate. Although As-Sa'a gate is relatively close to the beginning line of Tawaf, pilgrims that enter through the As-Sa'a gate would need to move in the opposite direction to the crowd flow to walk to the beginning line. This would cause delay in the duration of the pilgrims circumambulating the Ka'aba as counter flow occurs.

B.Occurrence of Bi-Directional flow at the gates.

The gates into the Tawaf area were not specified as entrances or exits. Thus, pilgrims are free to use any gates to enter or exit the area. This causes bi-directional flows to occur where pilgrims walk from two opposite directions interact with each other. During the Hajj season, the huge number of pilgrims walking in and out of the Tawaf area cause major congestions to occur at the gates. The bi-directional flow causes counter flows and cross paths. This may lead to collisions occuring during crowd panic situations.

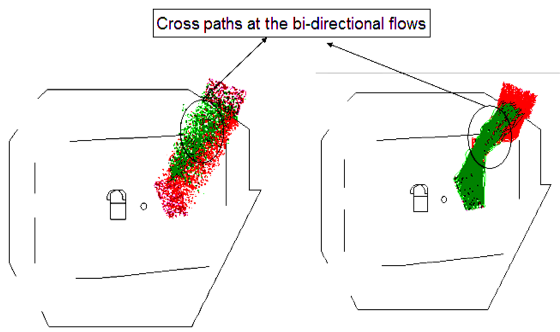
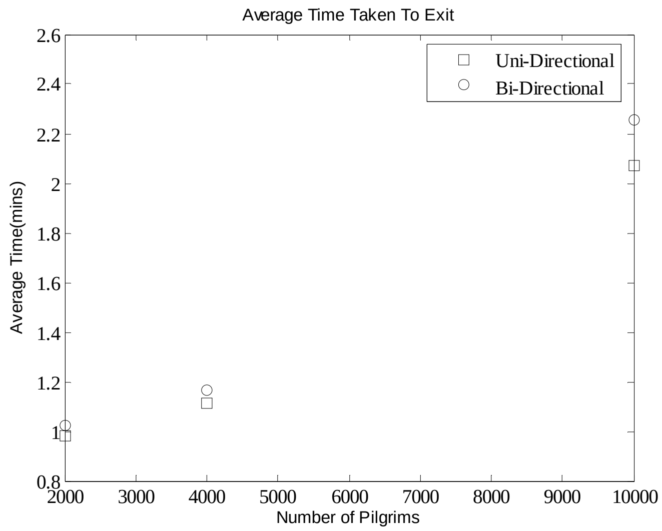


Fig. 2 Interactions of pilgrims in a bi-directional flow

Higher interaction among pilgrims from opposite directions would cause delay in the time for the pilgrims to exit the area. We would now investigate on the effectiveness of uni-directional flow at the gates in contrast to the bi-directional flow.

A simulation is done to measure the average time taken by pilgrims to exit the Tawaf area for 2000, 4000 and 10000 pilgrims repeatedly in uni-directional flow and bi-directional flow.



'ig. 3 Graph of Average Time Taken to Exit for 2000, 4000 and 10000 pilgrims

Fig. 3 shows the average time taken for the total number of)00, 4000 and 10000 pilgrims to exit the area respectively. We ın see that as the number of pilgrims' increases, the difference etween the average times taken to exit for pilgrims in both flows increasing. This is because as the number of pilgrims increases ı the bi-directional flow, the counter flow and interactions nong pilgrims from both directions increases causing delay to ıe time taken for the pilgrims to enter or exit.

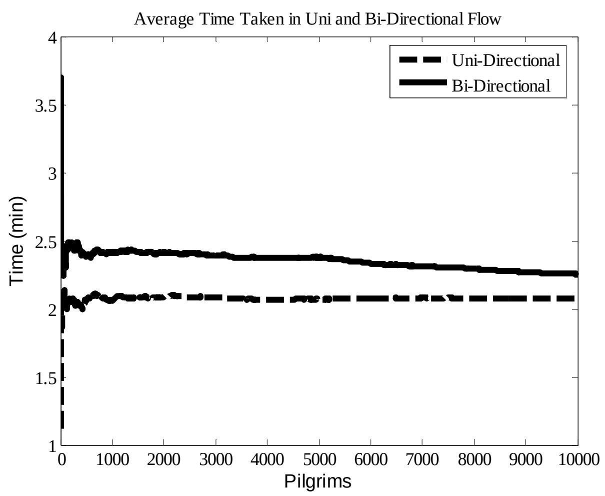


Fig. 4 Average time taken to exit in simulation run for 10000 pilgrims

Fig. 4 shows the comparison between the average time taken for 10000 pilgrims to exit the Tawaf area. We can see that the time taken is lesser when there is uni-directional flow. From the graph, we can see that in both flows, the time oscillates for the earlier pilgrims before reaching almost constant as the number of pilgrims increase to 10000. This happens due to the density that remains constant throughout the run as there is a balance in the number of pilgrims starting and ending the run. In the uni-directional flow, the time for the pilgrims to exit is less at the beginning and increases as the number of pilgrims increases. This happens because in a uni-directional flow the pathway will be empty for the pilgrims to walk in a single direction before becoming congested with pilgrims walking in the same direction. Hence, the earlier pilgrims will get to walk in their desired speed to their direction allowing them to reach earlier. As the number of pilgrims increases, the area becomes denser causing the speed of the pilgrims to decrease. Thus, all pilgrims would walk in an averagely similar speed causing their duration to exit the area relatively the same. The uni-directional flow is more efficient to reduce congestion at the gates by eliminating cross paths between pilgrims.

Thus, Al Fatah and Al-Sa'a gate would be specifically used only for exits as pilgrims could use both gates to perform their next ritual which is the Sa'e. This is done to ensure uni-directional flow at entrances and exits [11]. Cross paths between pilgrims entering and exiting the Tawaf area would not occur. The Al-Omra gate, King Abdulaziz gate and the King Abdulaziz gate would be used as entrances to the Tawaf area.

C. Relationship between the distance to the beginning line from entrance and the duration taken to complete Tawaf

Simulations were done to investigate the duration taken by pilgrims to complete Tawaf when they enter from 3 different gates; the Al-Omra gate, King Abdulaziz gate and the King Fahad gate. The Al-Omra gate is the furthest from the beginning line of Tawaf followed by King Fahad gate and King Abdulaziz gate.

The simulation done were based on [12] where waiting points are placed to guide pilgrims circumambulate the Ka'aba. Due to only 1000 pilgrims were simulated, we placed small waiting area so that pilgrims would walk in a dense situation.

Simulations were done separately for 1000 pilgrims where in each run, pilgrims enter the Tawaf area from the 3 different gates.

TABLE I
AVERAGE TIME TAKEN FOR 1000 PILGRIMS TO CIRCUMAMBULATE THE KA'ABA

Entrance	Al Omra	King Abdulaziz	King Fahad
Average Time Taken	24.8 mins	24.24 mins	23.7 mins

From the table, we can see that the time taken for the pilgrims to circumambulate using the 3 entrances is not much different to each other. Thus we can distribute the pilgrims evenly to all the exits. Information and briefing should be given to all the pilgrims so that they understand that the entrances do not play a very important role in the duration to circumambulate the Ka'aba.

III. DESIGN OF THE EXIT

Pilgrims that exit from the Al-Fatah gate and As-Sa'a gate would come into contact at the corridor towards the outer entrance. Thus, a proper exit has to be designed to minimize the interaction that occurs between pilgrims that exit the Tawaf area from both gates. A wall or barrier is built at the As-Sa'a gate in order to close the entrance and use the gate for exit.

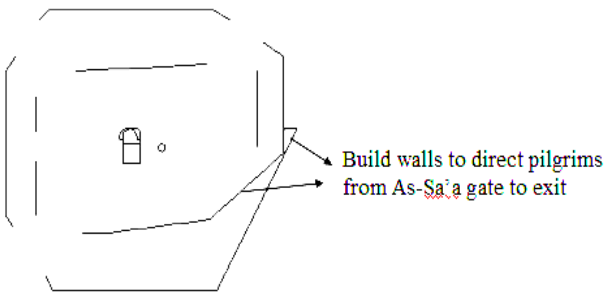


Fig.5 Walls built at As-Sa'a gate

A. Description of Simulation

Simulations were done to differentiate the duration taken by pilgrims to exit the Tawaf area with and without the columns. The efficiency of different designs of barriers would be discussed. Simulations were done for 2000, 4000 and 6000 pilgrims respectively. For simplicity, we do not take into account the 7 rounds of circumambulation done by pilgrims in the ritual of Tawaf area. We only discuss the time taken for pilgrims to exit the Tawaf. The starting area is determined from the beginning line of Tawaf where pilgrims would end their 7 rounds of circumambulation ritual. After passing the line, pilgrims would need to decide on which exit would he use to exit the area. Thus, our starting areas for the simulation would be the shaded area as shown in fig.6 below.

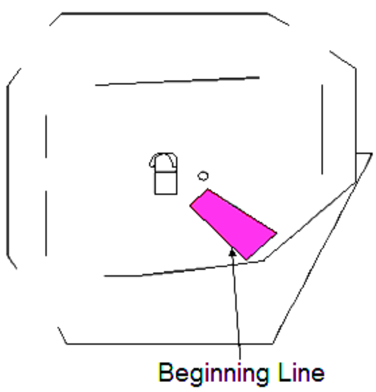


Fig.6 Position of starting areas

B. Various Designs of Exit

Based on the study in [10, 11], the simulations integrating the building of columns at the exits will be done to investigate the efficiency of the columns built at the exits. The purpose of the columns is to minimize the interaction between pilgrims from both exits. We would also compare the efficiency of building railings as opposed to building columns. We would investigate the time taken for pilgrims to exit when different kinds of barriers are placed to separate the pilgrims exiting from both exits. We chose three designs which are railings, big columns and small columns. We would also compare times with the time taken for pilgrims to exit the area when no barriers are placed.

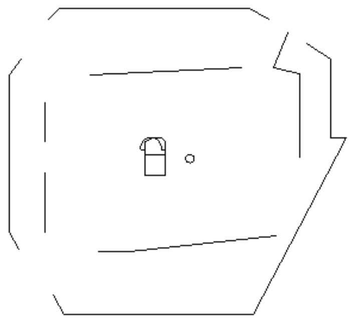


Fig.7 Design of Exit with railings

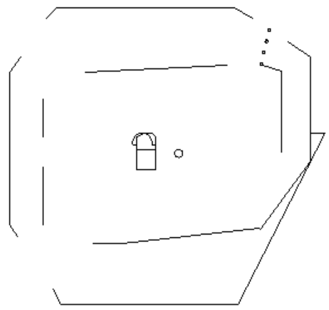


Fig.8 Design of Exit with smaller columns

Four columns with the diameter of 1.85m are placed within the distance of 8m from each other.

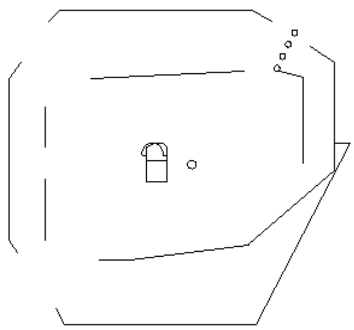


Fig.9 Design of Exit with bigger columns

Four columns with the diameter of 3.5m are placed within the distance of 4.75m from each other.

III. Result And Discussions

A. Comparison between time taken to exit with and without barriers

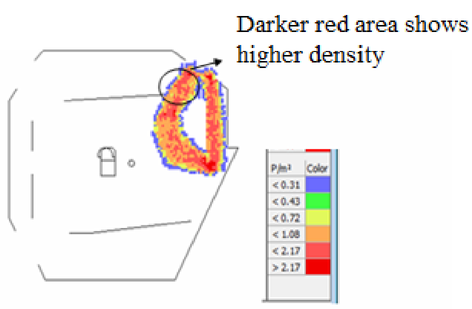


Fig.10 Simulation run for the bottleneck area without barriers.

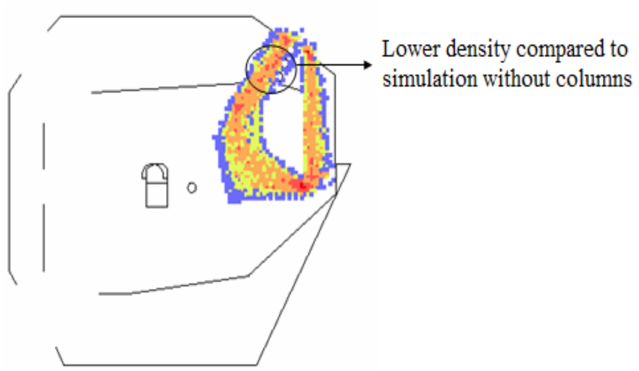


Fig.11 Simulation run for bottleneck area with columns.

Both figures above compare the densities of the exiting area. When the columns are built we can see that the area has lower density and are less packed when compared to the situation where the columns are not built.

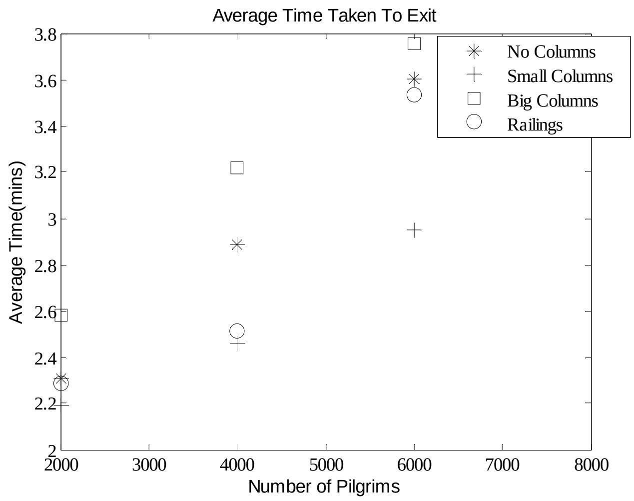


Fig.12 Average time taken for pilgrims to exit the Tawaf area for 2000, 4000 and 6000 pilgrims repeatedly

TABLE II
AVERAGE TIME TAKEN BY PILGRIMS TO EXIT THE TAWAF AREA

No of Pilgrims	No Columns	Small Columns	Big Columns	Railings
2000	2.3073	2.1943	2.5825	2.2881
4000	2.8867	2.46	3.22	2.5146
6000	3.6028	2.9514	3.7543	3.5336

From the Fig. 12 above, it is found that the average time taken for the pilgrims to exit the Tawaf area is shorter when columns are built to separate the pilgrims that are exiting from King Fatah gate and As Sa'a gate. Although there is no major difference in time in both situations, when we analyze the trail paths of pilgrims in the figures above, we can see that the interactions between pilgrims when the columns are built are lesser. Thus, when the columns are not built, the pilgrims from both exits come into contact and causes interactions and cross-paths among pilgrims from both exits. The interaction forces among pilgrims when columns are not built are higher which causes the path of pilgrims gets disrupted. The average time taken when smaller columns are built is the least which shows that smaller columns of diameter 1.85 are more effective in controlling the crowd. The permeable design not only acts as a wall to separate the paths of the pilgrims but it also allows pilgrims to use the other side of the path if their path is too dense. We can see when bigger columns are added, the average time increases. Bigger columns take up bigger space and acts as a wall that separate pilgrims from both sides of exit. The difference in time is also small as we are only investigating a small number of crowds. As can be observed, when the number of pilgrims increases from 2000 to 6000, the difference in time taken for the pilgrims to exit in all 4 methods are also increasing. Thus for bigger crowd, the difference in time would be significant.

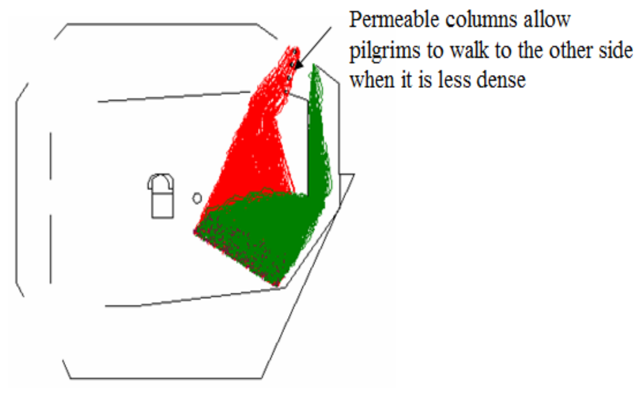


Fig.13 Trails for bottleneck with columns

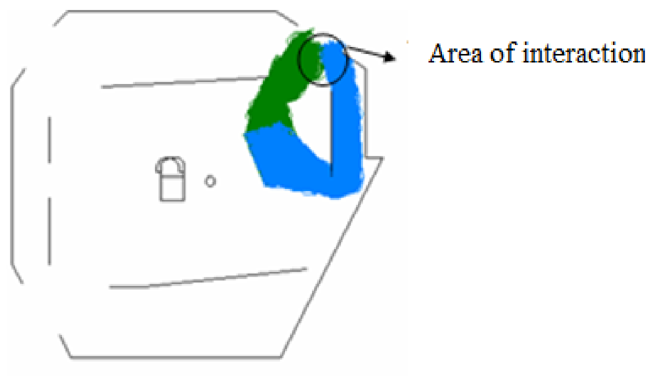


Fig.14 Trails for bottleneck without columns

B. Proposed design for exit

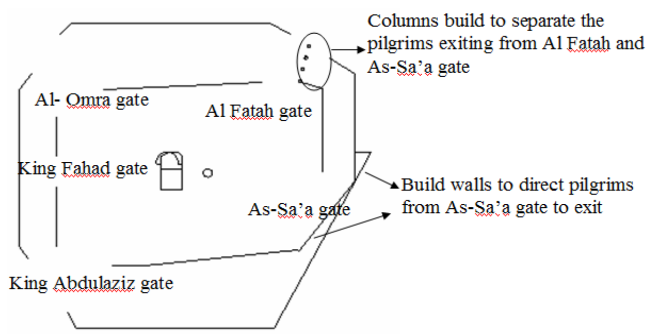


Fig.15 Proposed design at the exit.

From the results and discussions in section II, we propose the design of the barriers placed at the exit to be smaller columns of width 1.85 m placed with a 8m distance to each other.

IV. ISSUES AND LIMITATION

There are a few issues and limitations that arise in this study. These limitations occurred due to the limitations in the software. Also, the computational capabilities of the available computer used may not be sufficient to simulate a bigger number of pilgrims.

a) In the simulations of Section II B., we simulate the occurrence of uni-directional and bi-directional flow of up to 10000 pilgrims. This simulation did not have any waiting points placed for pilgrims to guide their walking path as the path is just a straight line to the exit. A bigger crowd could not be simulated due to restriction in the software.

b) In the simulations of Section II. C, only 1000 pilgrims were investigated in this study as when a higher number of pilgrims is taken the simulation is too long to complete and the system crashes. Even with 1500 pilgrims, although the simulation could be completed we could not obtain the statistical data. This happens because the simulations involve many waiting points causing the simulation to take a long time. Thus the results obtained may not be realistic when compared to the real life situation with a bigger number of pilgrims. In future, a similar study can be done for a bigger number of pilgrims to compare the current results with the results obtained. We also wanted to compare the average time taken when pilgrims use all 3 gates at once, but the simulation could not provide us with statistical data after the simulation has completed.

c) In the simulations of section III. A, we could only simulate up to 6000 pilgrims as the system could not generate the results for more than 6000 pilgrims.

d) We could study on the density and the flow rates of pilgrims but the data obtained were not sufficient to conduct the study.

V. CONCLUSION

From this study, restricting certain gates as entrances and others as only exits allows the smooth flow of pilgrims at the gates by ensuring uni-directional flow at the entrances and exits. We can see that building columns at exits allow pilgrims to complete their Tawaf smoothly. The purpose of building columns is to allow pilgrims from both exits to walk in their own paths and minimize the interaction between the paths of pilgrims from two different exits. Further studies can be done to discuss on the flow of the pilgrims and the capacity of the area to ensure a smooth flow of pilgrims during the peak season of Tawaf.

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