A NEW LAYOUT DESIGN FOR THE JAMARAT AREA (STONING THE DEVIL)

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الخلاصــة:

إحدى الشعائر الدينية التي يقوم بها الحجاج في منى هي رمي الجمرات على شاخص وتمثل رمزاً لرجم الشيطان. ويصل عدد الحجاج إلى مليوني حاج تقريباً يؤدون هذه الشعيرة في أوقات متفاوتة خلال الأيام الثلاثة المعينة للرجم في السنة الهجرية. لكن منطقة الرمي تصبح مزدحمة مما يجعل السقوط على الأرض أحد أهم أخطار السلامة. إن هذا الخطر، إضافة إلى عوامل سلامة أخرى، يستلزم إعادة تصميم منطقة الجمرات.

يطرح هذا البحث تصميماً جديداً لحل مشكلة السلامة، ويتضمن إنشاء ممرات أحادية الاتجاه (بعرض متر واحد)، وتحديد منطقة الرمي بمنطقة دائرية نصف قطرها 15 متراً. لقد أجريت تجربة لمعرفة الوقت المستغرق في رمي سبع حصوات من كل ممر مذكور واستخدمت المحاكاة لمعرفة وقت انتظار الحجاج لدورهم في الرمي، فكانت نتائج المحاكاة مشجعة لاعتماد التصميم الجديد.

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ABSTRACT

One of the rituals performed by Muslim pilgrims during Hajj near the Holy city of Makkah is throwing stones at a pillar target. This activity is a symbol of stoning the devil (Throwing Jamarat) as done by the prophet Abraham. The number of pilgrims reaches two millions but these arrive at the site at different times during a particular day. However, the area becomes congested around the structure of the target, which makes falling a major safety hazard. This factor beside others entails redesign of the Jamarat area. This paper presents a new design to solve the safety problems. It is suggested to install uni-directional lanes (one meter wide) and to restrict throwing to within a circular zone up to 15 meters in radius. An experiment was conducted to estimate the throwing time at each lane and used in a simulation model to estimate the waiting time. The results of the simulation encourage adopting the new design.

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INTRODUCTION

Around two million Muslim pilgrims perform Hajj yearly during the twelfth lunar Arabic month. The duration of Hajj activities commences on the ninth day and terminates on the twelfth. One of the activities done in Mina, adjacent to Makkah, is to throw small stones at a target and hit it seven times. The stones are natural and irregularly shaped, with a diameter of an imaginary sphere equivalent to approximately 1 cm. The original dimensions of the target are not published and estimated as three meters in height with a square base of nearly one meter in length. There are three structures as such named from west to east as: Small Jamrah, Medium Jamrah, and Large Jamrah (the plural of Jamrah in Arabic is Jamarat). All three targets fall in a straight line where the distance between the Small and Medium Jamrah is 135 meters and the distance between the Medium and the Large Jamrah is 225 meters. On the tenth day of the twelfth Arabic month, pilgrims throw at the Large Jamarah only. During the following two days, pilgrims throw at the three Jamarat in sequence, starting with the smallest and finish with the largest.

The number of pilgrims has increased significantly in the last two decades. A walking bridge, 80 meters in width, was constructed over the three Jamarat area to ease conducting the activity. The pillar target was extended in height and penetrated the bridge to access throwing from the top level. The Small and Medium Jamrah targets are encircled with a circular sink, at about waist height, to collect the stones. The Large Jamrah is surrounded with a semi-circular sink at the ground level and blocked at the other half while the top level is encircled with a circular barrier. The diameter of these sinks varies between 5 and 15 meters. The distributions of arrivals at the Jamarat area an each day (10th, 11th, and 12th) vary. This variation entails studying each day separately. The stones are collected from the ground of a nearby location called Muzdalifa. At each Jamrah, the pilgrims approach the target, reach to a convenient distance, and start throwing at it. Reaching a hitting distance is accomplished with difficulty. They are supposed to hit the target 7 times. In case they miss it, they try again. Therefore, they usually make sure that they carry more than seven stones for each Jamrah. Some pilgrims prefer to throw at a close distance to make sure they hit the target. The density of people increases as one approaches the target. Other people, mostly the older pilgrims [1], prefer to throw at a longer distance to avoid the crowded area for safety reasons.

It is worth mentioning that the Jamarat area has witnessed several fatal incidents over the past few years. The exact causes of these accidents are not well known. Obviously, one prime cause is cross-traffic in a highly dense area. Pilgrims finishing the activity leave, or fight their way out, while arrivals to the site fight their way in. This type of traffic creates unpredicted movement pattern which easily result in falling causing bodily injuries or fatalities. The other source of hazard is inadvertent impact by a stone on the face of a leaving person or the back of the head for a person engaged in the activity. About 28 percent of the pilgrims have been hit by a stone [2]. This accident may cause a serious eye injury or a temporary head inflammation. Aside from the safety hazards, there is an Islamic and ethical issue. In Islam, the bodies of different genders should not come into contact unless permitted such as the cases of the husband, father, son, brother, or uncle of a certain woman. Inadvertent body contact is frequent in crowded areas such as described in the Jamarat area; this causes embarrassment to both sexes.

The Jamarat problem has been addressed by some researchers. Ghandoorah [3] suggested building multi-level bridges and increasing the height of the target to penetrate through all levels. This is a practical solution but the number of levels should be determined scientifically. The obvious disadvantage is the cost of building the bridges. However, the Saudi government considers such expenditures worthwhile if a real solution is found. Barhamin and Muhrez [4] proposed to reduce the high density periods through scheduling of arrivals. This approach seems reasonable but requires a scientific study and enforcement. Al-Gadhi [5] noted that the density of people around the target should be encouraged to be uniform. This suggestion requires directing the attention of pilgrims to lower density spots. However, such a solution requires a communication language understood by the different native tongues and it requires the mechanism of implementation. Al-Gadhi also recommended to increase the area of the basin that collects stones to increase the throughput of pilgrims. The disadvantage of this design is to increase the distance between the target and the throwers. It has been reported that more than 82 percent of the throwers actually hit the target despite permission by their school of thought to throw in the basin for some schools. So, increasing the distance from the target would make it harder to hit the target and may require more time to complete seven hits. As a result, the area becomes more crowded and more dangerous.The throwing time in his study [5] averaged 27 seconds and was found to be independent of either the distance from the basin or the concentration of pilgrims. This is in contrast to the results found in this study in which case the distance was a significant factor. The change in the shape of the basin from circular to elliptical while maintaining the same area resulted in a negligible increase in the throughput [5]. Selim and Al-Rabeh [6] formulated a mathematical model to minimize a cost/penalty function. They divided the area into three parts: the throwing area, the waiting area, and the area used for reaching towards the target. The objective function could be to minimize the number of waiting pilgrims. The output of the model determines the inflow rate to the area which implies controlling the arriving pilgrims.

This study presents an experiment of throwing stones at a target at various distances and introduces a new layout design for the Jamarat area. The new layout design is expected to smooth traffic and to reduce, or eliminate, safety hazards and ethical problems. A model is developed by AweSim software to simulate the new design. The results of the simulation model with recommendations are stated.

NEW LAYOUT DESIGN

The problems of conflict in flow direction, hitting the face with stones, and body touching could be solved by controlling the flow so as to be uni-directional. This control is possible by installing parallel barriers extended along the line joining the three Jamarat. Figure 1 shows the new layout design for a single Jamarah. Pilgrims enter a certain lane from the west side and proceed to hit the targets sequentially in day 11 and 12 of the month and they proceed directly to the Large Jamrah on day 10. Once entered in the lane, there is no chance to change it. The width of the lane should be wide enough to allow people stand and perform the activity at the side closer to the target and to allow people to walk freely along the side further from the target of the lane. This movement is expected for pilgrims finishing hitting the target or for new arrivals reaching for a vacant slot to hit. This design is feasable even during panic, since, due to some reason, people still know the direction of movement. Evacuation of pilgrims starts by stopping the incoming traffic and asking them to return to their origin and utilizing the full width of the lanes to vacate the pilgrims already inside the throwing area in a unidirectional movement. This procedure, if applied to the new design, should reduce the severity of accidents.

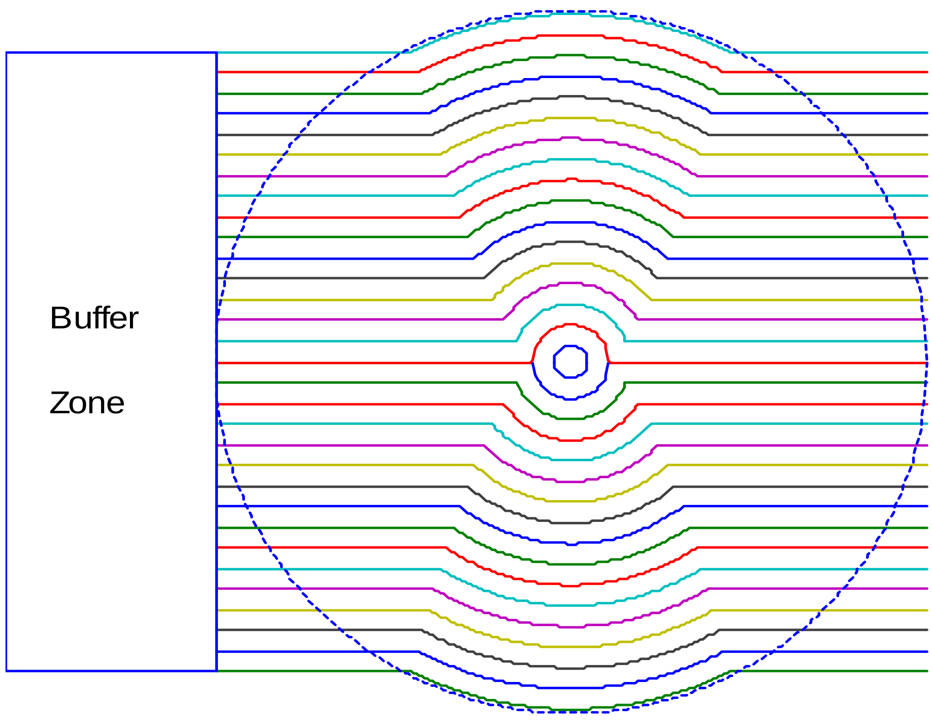

Figure 1. New layout design showing 30 lanes. The central circle represents the pillar target, the second circle represents the basin to collect stones, and the dotted circle represents the throwing area.

The width of the lane could be determined by two body dimensions. This issue is related to body dimension, called anthropometry, in the area of Ergonomics or Human Factors Engineering. The relevant body dimensions are, first the maximum body depth (could be at the chest area or the hip area) for a standing person facing the target and engaged in throwing. The other dimension is the maximum body breadth (could be at the shoulder level or the hip level) for a person walking behind the throwers in a certain lane. Relevant body dimensions for different Muslem origins and gender should be obtained either from the literature or by collection with the correct proportion to make a proper design for the lane dimensions. This author has collected body dimensions of male Muslims with different origins [7]. The results of the study is used here as an example since it lacks female body dimensions, the sample size is small (408 persons), and the proportions of different origins do not match the actual pilgrims proportions. With this precaution in mind, some statistics are used in the concerned design. In Ergonomics, it is satisfactory to accommodate the majority of the population in a certain design, not necessarily all of them. The usual statistics of body dimensions used are small and large percentiles with the average value used in limited applications. In Al-Haboubi's study [7], the 95th-percentile of maximum body breadth is 54 cm and the 95th percentile of the maximum body depth is 31 cm. The sum of both values determines the required width of the lane, *i.e.* 85 cm. To be in the safe side, and to take into account the thickness of the barrier, the total width of the lane is increased to 1 meter.

In the experiment that will be discussed later, it was observed from video films that at the beginning of the throw the hand is raised above the head level and it is almost extended at the shoulder level towards the end of the throw. So, the area immediately in front of the thrower, and at arm's length, should not be occupied, to enable an accurate hit. Since the Jamarat space is limited, it is not appropriate to reserve an arm's length ahead of each pilgrim. To solve the problem of utilizing space and at the same time provide space for the thrower, the idea of different elevations for each lane emerges. The difference in elevations between successive lanes should be large enough to allow the hand of a short person to clear the head of a tall person standing in front. The relevant statistics in this case are the 95-th percentile of stature (for a tall man in front) and the 5-th percentile for the shoulder height while standing (for a short woman behind). The results of Al-Haboubi's study [7] revealed the following relevant statistics: the 95th-percentile of stature is 182.2 cm. Body dimensions for Muslim females are not available for many countries. The 5-th percentile of shoulder height for Algerian Muslim women has been found to be 122.1 cm [8] and is computed for Egyptian women as 117.7 cm. [9] assuming a normal distribution. Taking the middle value (120 cm.) between both nations as a representative 5-th percentile of shoulder height for Muslim women and the 182.2 cm as a representative 95-th percentile for stature of Muslim men would make the difference approximately as 60 cm. This value represents the difference in lane elevation. In the case this recommended height difference is costly or seems to pose a falling hazard then it may be ignored, however, the pillar should be extended to make it visible to short pilgrims. In fact, any height difference as short as the step risers is better than nothing. Figure 2 shows a side view of the recommended layout design. This design entails extending the height of the target (pillar) to match the height of the person standing at the highest and furthest from the target. Such arrangement would reduce or eliminate hitting the head by a stone thrown from behind where the horizontal distance from the target is reasonable.

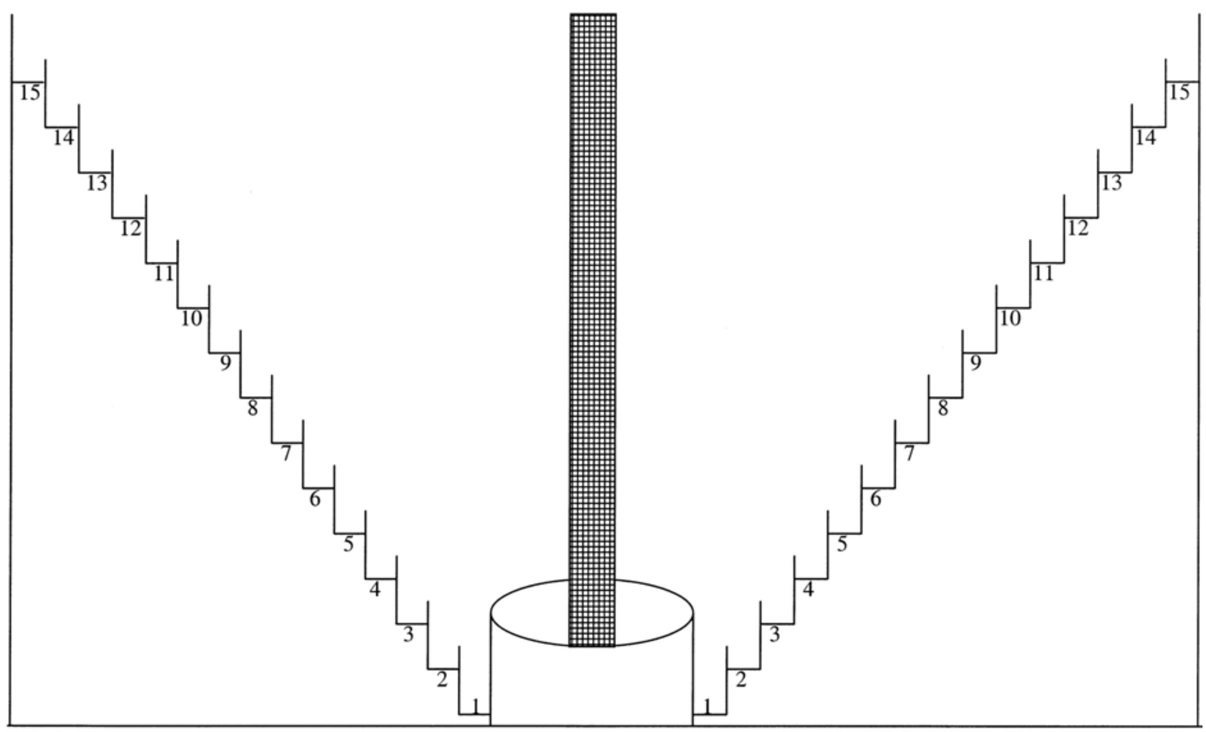

Figure 2. Cross-section of the new layout.

This maximum recommended distance is 15 meters as shown from the results of the experiment that will be discussed later. Accordingly, the throwing area is circular and limited to 15 meters in radius where the center is the target. The radius is selected based on experimental stoning of a physical model, constructed at the university campus, at various distances, as will be shown later. This study is confined to simulating a single target to check the feasibility of the design. Simulation of all three targets is left for further work.

The throwing area is circular and symmetrical along the line joining the three Jamarat. Hence, one side of the layout is shown in the figure. A net installed along the line of symmetry passing the middle of the pillar would protect against stones thrown from the opposite side. The target is proposed to be circular with one meter in diameter. The target is surrounded with a circular basin, 3 meters in diameter, allowing the stones to fall in a one meter ring or three forearm lengths as mentioned by religious scholars [10]. The height of this basin and the barriers separating the lanes should not obscure the view of the target and obviously should not exceed the height of people. At the same time, it should not be low enough for easy crossover to avoid falling in to the safety hazards mentioned earlier. It is recommended to make the height of the barrier equivalent to the median height of the users' (males and females) waist. The material of the barrier should be strong and the thickness as narrow as possible to increase the utilization of the one meter width dedicated for the lane.

The total number of lanes considered is 15 contained in a semi-circular area that will be called "the throwing area". The number of people in this area should be controlled to avoid congestion. Hence, the capacity of each lane should be estimated. The capacity of each lane is estimated from the maximum body breadth of users. Since people are facing the target side by side, the appropriate statistic is the average value of this body dimension. Again, the reported values by Al-Haboubi [7] are used as an example. The average of the maximum body breadth was 48 cm which seems reasonable for the user population. To be in the safe side, the distance occupied by a person conducting the activity is assumed to be 50 cm, *i.e.* 2 cm more than the designated average. Dots are placed on a grid (not shown, scaled 0.5m. by 0.5m.) representing a standing pilgrim to estimate the capacity of each row. The capacity for each lane is estimated by counting the dots along each row and shown in Table 1. The number of pilgrims in each lane should not exceed the respective capacity. To ensure this ceiling is not violated, vertical bars should be placed with 50 cm. inter-distance along the barrier of each lane. Each slot is dedicated to a single person for throwing stones. A recommended height for these bars is the 95-th percentile height of males. The capacity (maximum number of pilgrims in the throwing area) could be controlled by a counter, such as those found in train stations, and another device at the end of the lane to decrement the number of users for each departure. The number of people inside each lane should be displayed above the entrance of each lane. It should be emphasized that the lane segment further from the target should be used for walking only. This part of the lane should not be used for throwing so that the throwing activity becomes independent. If two rows of pilgrims are formed for throwing in any lane then the throwing times for later pilgrims in that row would depend on the time consumed by former pilgrims which means the service is not performed in parallel as intended. An example of the effect of dependency among pilgrims is a slow person or a person delegated to throw for others. Such persons would delay pilgrims succeeding them if there is no way out. However, making the track behind throwers for walking purposes only guarantees independence.

Table 1. Estimated Capacity for Each Row

Row	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Capacity	64	64	63	62	61	59	58	57	55	51	49	45	41	32	27

The concept of controlling the number of throwers implies that arrivals to the Jamarat area may wait for their turn and stand in a queue. The beginning of the queue should be at some distance from the entrance of the 'throwing area' to direct pilgrims to available slots. Direction of pilgrims to a certain lane should not be communicated verbally since there are many spoken languages in the Hajj event. It may be communicated by a green light similar to the traffic light and another red light to indicate the line is at capacity and no one is allowed to enter. A recommended distance for directing pilgrims is an arbitrary 10 meters which would result in an area called ' the buffer zone' before the throwing area. An entrance to the buffer zone should be as wide as the width of the throwing area to avoid forming a bottle neck as shown in Figure 1. Although the queue may consist of several parallel lines across the entrance, in simulation it will be considered as a single queue without loss of generalities. The simulation model requires the distribution of throwing times which is not available in the literature. Hence, an experiment is conducted to establish the distribution.

EXPERIMENT

The objective of the experiment is to find the distribution of throwing time at various distances. The site of the experiment was selected outdoors at King Fahd University for Petroleum and Minerals (KFUPM) campus to mimic the actual situation. Two manholes were placed on top of each other to resemble the pillar target. These structures were made of concrete, with a rounded base of 1.6 meter diameter and are 3.4 m, in total height. Fifteen markers were place in line and one meter apart to show the distance from the target. Subjects stand next to each marker to throw at the target. The maximum throwing distance is 15 meters which is believed sufficient for the study since the stones are small. Faculty members, staff, and students (all males) at KFUPM were invited, including non-Muslims, to participate in the experiment. The number of volunteers participating is 30 faculty members, 4 staff members, and 70 students. The faculty members and staff (mean age is 39.3) are grouped separately from the students (mean age is 21.9) because of different ages. The time for the experiment of each subject were determined based on his convenience but was restricted to between 1:00 and 5:00 in the afternoon to reduce the variation in temperature and sunlight direction.

Time was measured individually at each marker selected randomly. The volunteers wear their usual Arabic or western dress, but they are supposed to wear light clothing at the shoulder area and they were asked to remove the Arabic overhead wear to allow throwing freely. They hold a bunch of stones similar in size to those found in Muzdalifa, stand next to the selected marker facing the target, and start throwing after receiving a signal from the experimenter who start measuring the time with a digital stop watch. The subject is supposed to hit the target seven times and be responsible for counting the number of hits, as is done in an actual situation. When he makes the seventh hit, he raises his voice uttering 'seven' to signal finishing the throw trial. Another distance is chosen randomly and the procedure continues till all 15 distances are tried Statistics and the distribution of throwing times at each lane and for both groups, students and faculty, are shown in Table 2. It is observed that the mean times increases as a function of distance. The longer time is caused by the fact that the stones cover a longer distance but more importantly due to the increase in the number of misses. The effect of the number of misses is clear by comparing the results for both groups. The mean throwing times for faculty is consistently greater at each distance and their misses are greater. So, the effect of age is reflected by the accuracy of hitting the target which consequently affected the throwing time. Further analysis of the data is not required in this study since the objective is to find the distribution of throwing times at each distance. The distributions were found by constructing histograms for each row and using the chi-square test for both groups as listed in Table 2.

Table 2. Means and Distributions for the Throwing Time (seconds) and Mean Number of Misses at Different Distances for Faculty Members and Students. The shown parameters are as found by the chi-square test where the parameters in the AweSim model for the lognormal distribution are the average and standard deviation of the throwing time.

	Faculty			Students		
Lane	Mean	Distribution	Misses	Mean	Distribution	Misses
1	8.6	Normal (8.6,2.1)	0.0	7.6	Lognormal (2.0,0.192)	0.0
2	9.1	Gamma (0.38,23.79)	0.0	8.0	Lognormal (2.07,0.179)	0.0
3	10.2	Lognormal (2.3,0.189)	0.1	9.0	Normal (8.96,1.407)	0.0
4	10.6	Lognormal (2.34,0.221)	0.0	9.4	Gamma (0.31,29.96)	0.0
5	11.3	Lognormal (2.4,0.232)	0.1	10.4	Normal (10.4,1.965)	0.1
6	11.7	Lognormal (2.44,0.21)	0.1	10.8	Gamma (0.36,29.7)	0.2
7	13.2	Lognormal (2.55,0.243)	0.2	11.6	Normal (11.6,1.881)	0.7
8	15.4	Lognormal (2.69,0.3)	0.7	13.2	Gamma (0.47,28.16)	1.3
9	16.2	Lognormal (2.74,0.292)	0.9	13.7	Gamma (0.44,31.35)	1.4
10	21.0	Lognormal (2.96,0.387)	1.6	15.2	Gamma (0.72,21.21)	2.1
11	22.2	Lognormal (3.03,0.366)	2.4	17.0	Lognormal (2.79,0.27)	2.4
12	24.1	Lognormal (3.13,0.33)	2.5	19.8	Lognormal (2.94,0.29)	3.2
13	30.9	Gamma (5.2,5.94)	4.4	23.4	Lognormal (3.1,0.327)	4.2
14	37.5	Lognormal (3.46,0.552)	8.6	25.1	Gamma (2.76,9.11)	5.5
15	44.6	Gamma (11.72,3.8)	10.1	31.4	Gamma (4.12,7.62)	7.3

SIMULATION MODEL

AweSim simulation software is used to simulate throwing the stones. The objective of constructing the model is to analyze the waiting time at the entrance for a given arrival process and the queue length. The inter-arrival times are estimated from a figure showing the percentage of pilgrims throwing stones in the Largest Jamrah at the 10-th day of the year 1983 against the time of the day [11]. Such data are not published yearly but it is believed that the distribution of arrivals is maintained. The time scale was divided into 30 minute intervals. Vertical lines were extended at the time marks equivalent to the appropriate percentages that formed successive trapezoids. The sum of the areas of these trapezoids should be 1 for the given figure so that it may be considered a density function as known in Statistics. The percentage area for each trapezoid (Table 3) multiplied by the total number of pilgrims represents the number of pilgrims arriving within half an hour. The inter-arrival time is considered constant for each 30-minute period and equal to 30 divided by the estimated number of arrivals during the half-hour interval. A dedicated network is constructed to generate or create arrivals that are used in the major network model.

Table 3. Estimated Percentages of Arrivals to the Largest Jamrah at Day 10 of Year 1983. Adapted from Angawi and Yunis [11]

Start of Period	Percentage	Start of Period	Percentage	Start of Period	Percentage
5:30	2.15	10:30	6.30	3:30	0.65
6:00	4.00	11:00	5.45	4:00	0.65
6:30	5.45	11:30	4.55	4:30	0.70
7:00	6.80	12:00	3.55	5:00	1.30
7:30	7.40	12:30	2.55	5:30	1.95
8:00	8.65	1:00	1.60	6:00	2.30
8:30	7.05	1:30	1.30	6:30	0.35
9:00	7.15	2:00	1.15	7:00	0.20
9:30	7.30	2:30	1.15	7:30	0.45
10:00	6.90	3:00	0.90		

In the major network, entities are created according to the inter-arrival process described. These entities are divided into two categories: pilgrims who throw Jamarat for themselves only and pilgrims who throw for themselves and on behalf of others. So the time consumed in throwing (the service time) has to be multiplied by a factor that represents the number of delegating pilgrims plus the delegated person. The distribution of the number of delegating pilgrims could not be determined from the literature and will be arbitrarily assumed to be uniform with the parameters 2 (minimum is one delegating pilgrim plus the delegated person) and 4 (assuming the maximum number of delegating pilgrims is 3 plus the delegated person). The arriving entity proceeds to a queue node to wait if all servers are busy. A server is busy means a space for one person is occupied by a pilgrim in the actual system. The number of servers in each spot inside the circular area are estimated based on the distance from the target. The dots representing pilgrims mentioned above are used again to estimate the slots at equal distances from the target. The distance from the target varies between 1 m, and 15 m, as shown in Figure 1. Hence, the number of dots are counted easily using the circular lines for each distance. These dots represent the number of servers at each distance in the simulation model. In the model, the number of servers are doubled to take into account the other half of the layout shown in Figure 1. Thus the total number of available slots (servers) is 1556 as shown in Table 4.

Table 4. Number of Slots (Servers) Considered at Each Distance

Distance (m)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Servers	14	30	42	54	62	78	94	110	118	138	142	150	166	178	190

An arriving entity proceeds to a service activity if a slot is available without waiting in the queue. Preference is given to shorter distances if a choice is available. This is based on the expected behavior of pilgrims in choosing to hit at a short range. The service time is selected randomly according to the distribution found for each distance. In addition to the service time, the walking time from the entrance to the available slot and from the slot to the exit should be considered. It is difficult to estimate this time since it depends on the walking speed, the density of people in each lane, and the flow rate as known in Traffic Engineering. The stated model is not established to estimate these variables, hence the walking time cannot be estimated accurately. Instead of estimating the walking time, it will be assumed taking different values (0.75, 1.0, and 1.25 minutes) deemed reasonable to cover the 30 m. length of the lane plus the 10 m. for the buffer zone. The corresponding walking speeds are 3.2 kph, 2.4 kph, and 1.9 kph, respectively. These speeds are considered reasonable for the given situation. The service time for delegating pilgrims is taken into account at this stage. Then the entity proceeds to a collect node (to collect statistics) and is terminated.

RESULTS AND DISCUSSION

The throwing times (service times) for faculty members and students (Table 2) are used to run the simulation model separately as an example. The groups were separated due to the age difference, which may affect the throwing times. Results of tests of hypotheses of the means of the two populations revealed that the mean throwing time of faculty members is significantly higher than the counterpart value for students. For the sake of the example, the percentages of arrivals to the Largest Jamarah (Table 3) is used to introduce pilgrims to the model. The percentages are multiplied by the number of pilgrims intended to perform service. The number of considered pilgrims ranges between 500 000 and 1 000 000, with 100 000 increment. The model was executed 30 times for each number of pilgrims considered at three different walking times (0.75, 1.0 , and 1.25 minutes) for both groups (faculty and students). Each set of 30 runs lasted between 2 to 4 hours in a Pentium II personal computer. The measures of performance considered are the average waiting time in the queue and the maximum queue length. Both of these measures are inter-related. The first measure records the waiting time that leads to frustration in case it gets long. The second measure keeps track of the size of the waiting crowd at any moment which becomes a source of security and safety hazards if it reaches the frustration level. The results of the simulation runs are shown in Figures 3 to Figure 6.

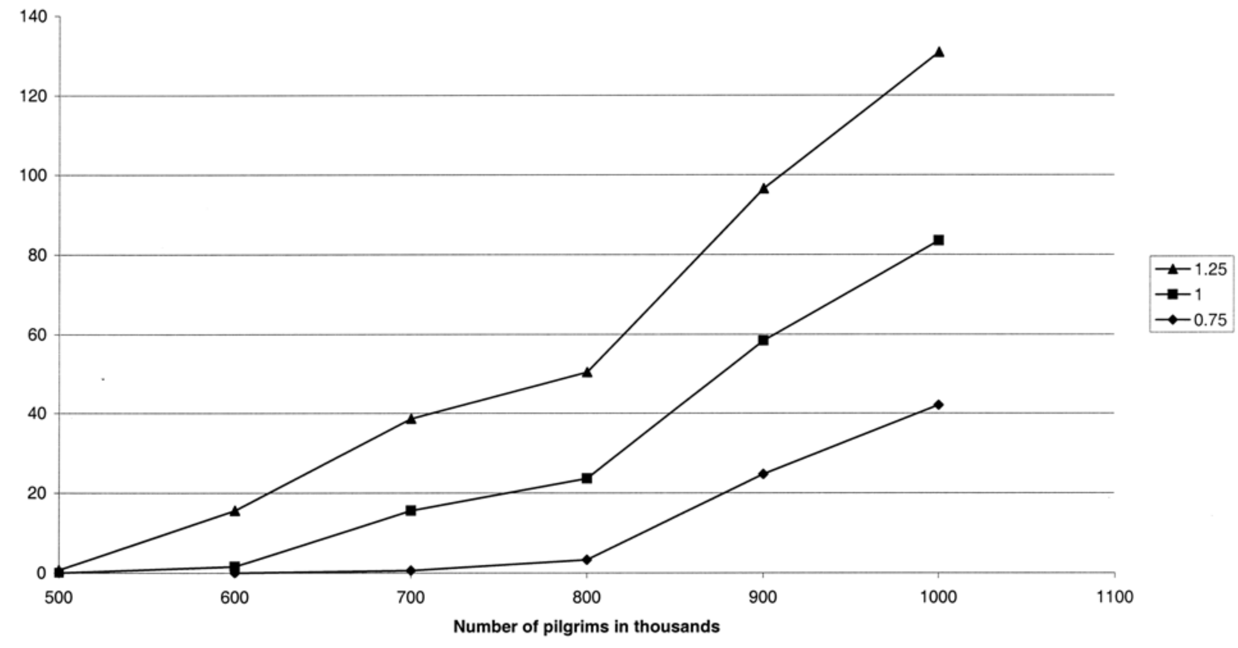

Figure 3. Average time (min.) in queue at different walking times (0.75,1.00, and 1.25 min.) for 30 runs, using faculty data.

The results show an increase in the average time spent in the queue as the number of pilgrims increases as shown in Figure 3 and Figure 4. Longer walking times make the average delay in the queue longer and the difference in the delay becomes larger at higher number of pilgrims. The effect of walking time is consistent across all pilgrims and seems to be critical since the chosen walking times are relatively close. Accordingly, further research has to be conducted to analyze the walking behavior of pilgrims using the suggested layout design. The delay times for faculty members is slightly longer than that for students since the throwing time is longer. This result reflects the effect of age on the delay.

The maximum average queue length of the 30 runs are shown in Figure 5 and Figure 6 at different walking times. The trend in both these figures are similar to those shown for the average waiting time for both groups. This measure of performance provide an estimate of the waiting area required. For example, if we estimate the average area occupied by a pilgrim standing in the queue by 0.25 m^2 (0.5 m. by 0.5 m.) then the waiting area may be estimated easily. However, it is essential to plan for small waiting crowds since large crowds can cause security problems and safety hazards. This is possible by providing service with little or no delays, say below 5 minutes. The points satisfying this criteria are shown in Figure 3 and Figure 4 adjacent to the zero average time.

The utilization of the slots (servers) close to the pillar target is high with respect to the given capacity and it decreases as the distance becomes longer. This observation for each set of 30 runs is in effect due to the preference given in the model for available slots closer to the target pillar. The results of the utilization runs are not shown because of its size.

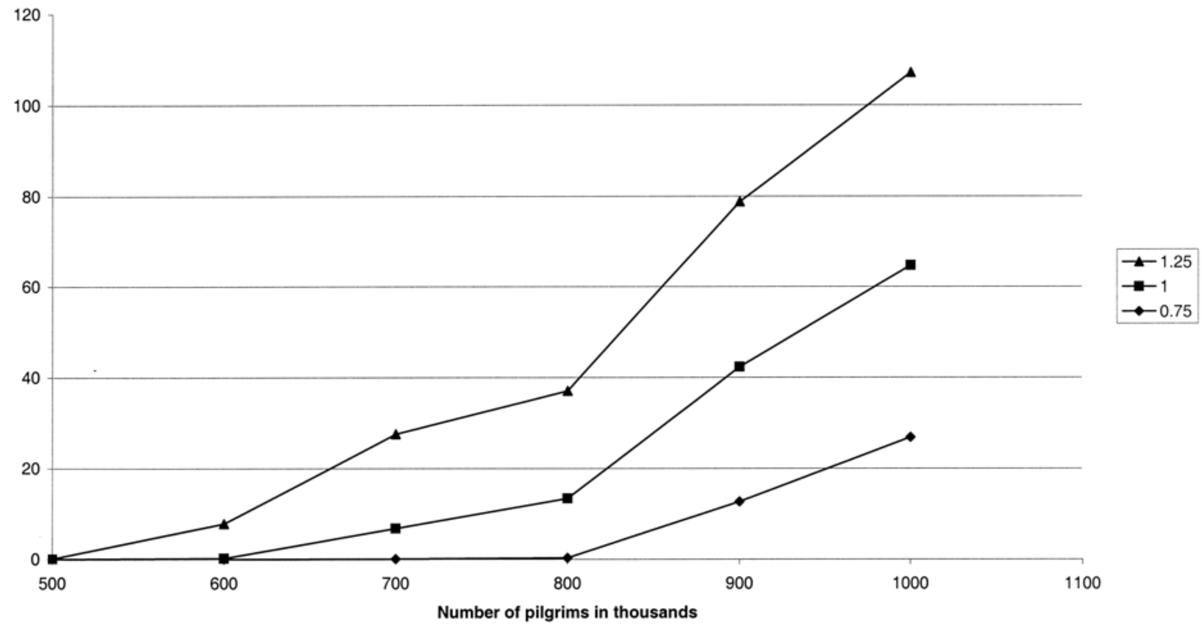

Figure 4. Average time(min) in queue at different walking times (0.75,1.00, and 1.25 min.) for 30 runs, using students data.

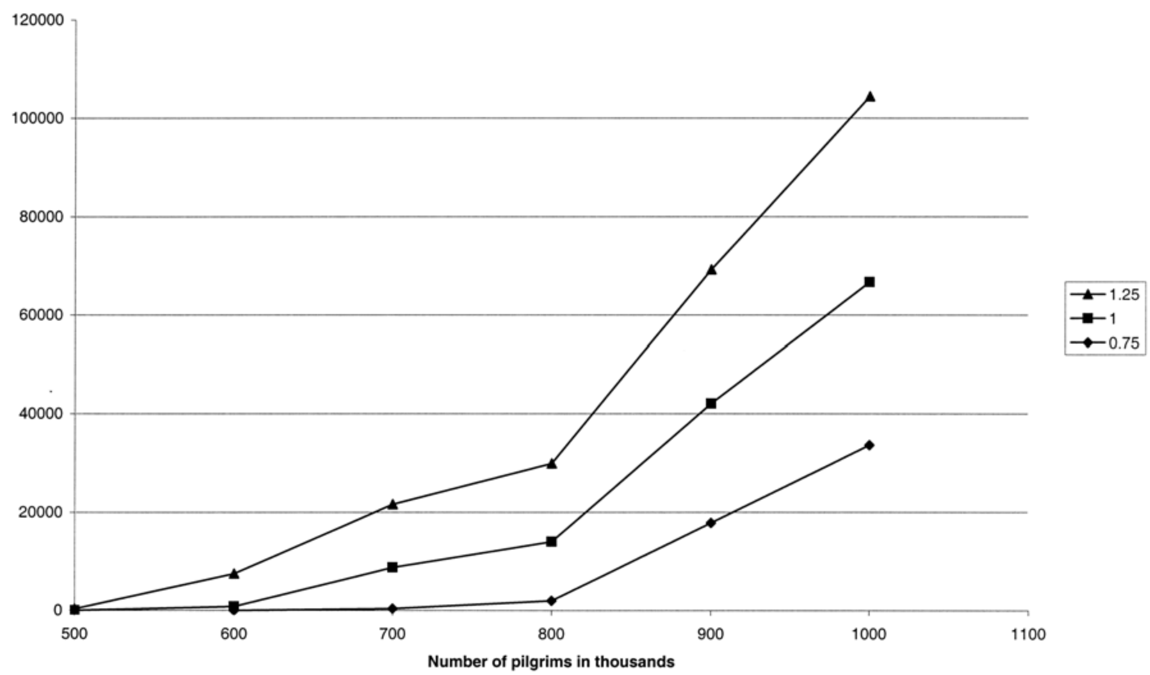

Figure 5. Maximum average queue length of 30 runs at different walking times (0.75,1.00, and 1.25 min), using faculty data.

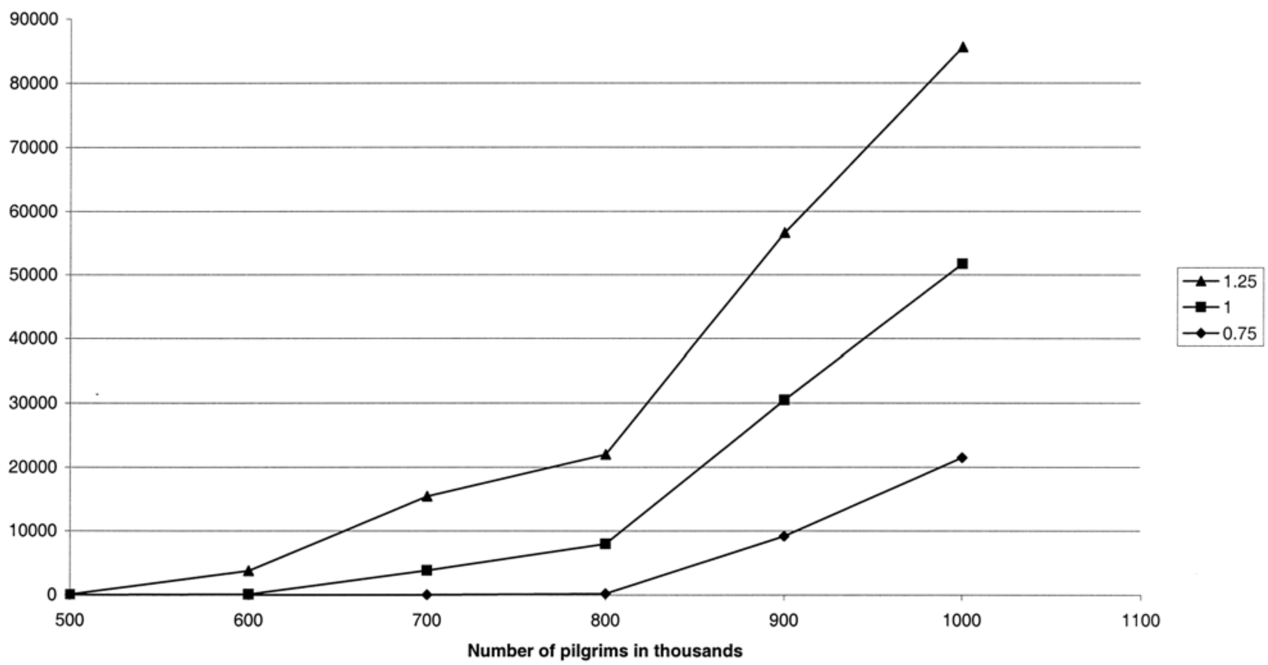

Figure 6. Maximum average queue length of 30 runs at different walking times (0.75,1.00, and 1.25 min), using students data

In the case representative data is available, including different ages, gender, and origins, such simulation runs would help in deciding the complete structure required. For example, if we assume the total number of pilgrims is 1 800 000, and further, assume the faculty data is representative for the whole pilgrims, we found out that when the walking speed is 1 min. then one new layout design can handle 600 000 pilgrims since the average waiting time and the maximum queue length are close to zero. Thus, the total number of pilgrims divided by the capacity of one design results in 3 new layout designs needed. The structure of these designs should be vertical and the target pillar should be extended to reach all levels. As it stands now, there are two levels, the ground level and another one made as a bridge. So, the concept of multi-levels exist but the number of levels should be determined. It should be noted that this study does not analyze the application of the new design in depth. For example, the semi-circular sink shape of the Large Jamarah at the ground level is ignored. The objective of the paper is just to introduce the new design and show its feasibility.

LIMITATIONS

1. Relevant body dimensions are taken from a small sample of male muslims. Taking into account the size of the Hajj event, such dimensions should be taken from a large sample size of each origin and for both genders. This task is by itself a major research work that entails the participation of officials from many countries and requires a high tagged budget .
2. The throwing experiment does not take into account the crowding effect since it was performed for individual persons.
3. The sampled populations (students and faculty members) do not necessarly represent the actual population for the following reasns:
   - Higher education level of the participants.
   - The age distribution differs between the pilgrims and the human subjects participated in the experiment.
   - Females were not considered in the experiment
   - The spritual feeling of pilgrims is a factor that cannot be imitated.

   The inclusion of these factors is important and entails a major task that should be done. It is really difficult to run an experiment that represents the actual situation with regard to density of people, age , gender, education, and origin. Actual observation of the throwing times does not help without the new design. So, this issue remains in a circle with no obvious treatment.

4. The data for the arrival process is about 20 years old. However, it is believed that the pattern of arrivals remains unchanged over the years, *i.e.* the percentage of arrivals during a given period of time is assumed constant. This assumption makes sense since some followers of certain schools of thought are restricted to throwing in the afternoon while others are allowed to throw all day long.

5. The distribution of the number of delegating pilgrims is assumed uniform. The author tried to estimate the percentages of delegating and delegated pilgrims from Al-Hajj Research Center Summary (1990) about the Jamarat activity but the statements in this regard were unclear.

CONCLUSIONS

This study proposes a new layout design for the Jamarat area. The design is modeled and simulated for two age groups (faculty and students), three waking times (0.75, 1.0, 1.25 min.), and 6 different number of pilgrims (half a million to one million at 100 000 increment). The results of the model reveal the feasibility of the new design. It seems, although this should be tested with representative data, that one or two more levels are needed to absorb all pilgrims (around 2 millions) and solve the safety hazards mentioned earlier. The cost of the new design could be considerable, especially with the graded lanes, but I am sure that the Saudi government is willing to spent money for real improvements during Hajj.

Concrete conclusions may be stated after further research is conducted to prepare representative data for body dimensions and throwing times, to study the behavior of walking in a prototype, the arrival rate to the site, the incidents of delegation to other pilgrims, and the simulation of all three Jamarat concurrently.

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