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A NetLogo Model for Ramy al-Jamarat in Hajj

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ABSTRACT

Millions of Muslims gather in the holy city of Makkah annually to perform Hajj (Pilgrimage), a religious obligation for every affording individual. Ramy is a ritual of Hajj in which every individual is required to throw stones at Jamarat pillars in a confined area in a limited time period. In this article, we present a model of ritual of Ramy on Jamarat bridge. The model is developed in NetLogo and can be used to simulate Ramy with user-defined parameters. Some of these parameters include Jamarah view range, hitting range of Jamarah and time to do Ramy. Various shapes of Jamarah pillar are analyzed for queuing of Hajjis during Ramy including circle, ellipse and deformed ellipse. The results show that the existing elliptical shape of Jamarah pillar outperforms other shapes for queuing of Hajjis.

KEYWORDS: Crowd simulation, Hajj, Ramy, Stoning of devil, Jamarat, NetLogo

1. INTRODUCTION

Hajj (Pilgrimage) is an important pillar of Islam. It is performed by physically visiting the holy city of Makkah in Saudi Arabia and performing certain rituals. It is mandatory for every affording Muslim man and woman to perform Hajj once in lifetime. Hajj is performed from 8-12of Dhu'l-Hijjah, the last month of the lunar Islamic calendar.

The number of Hajjis(pilgrims) has increased tremendously in the last few decades. According to Saudi Hajj Ministry, the total number of Hajjis in 2012 was 3.16 Million [1]. A mandatory ritual of Hajj is Ramy al-Jamarat (stoning of the devil); also called Rajm. Ramy is performed on three days of Hajj. On 10th of Dhu'l-Hijjah seven stones are hurled at large pillar (Jamarah al-Kubra) only while on the next two days, Hajjis are required to throw seven stones at each of the three pillars (Jamarat). A bottleneck in this ritual is a very limited time to perform it. On 10thof Dhu'l-Hijjah, it must be performed from sunrise until noon and on other two days, it must be performed from noon until sunset. Thus the minimum time required to complete Ramy in a day is about 5.5 hours. Till 2006, Jamarat bridge, on which Ramy is performed, had a single tier above ground level and in the past few years, hundreds of people have lost their lives due to crowd congestion during the ritual. A number of incidents of stampede in Jamarat area have claimed precious lives over the years – 1,426 Hajjis in 1990, 251 in 2004 and 364 in 2006, to name a few[2,3].

In 2006, the old Jamarat bridge was demolished and construction of new multi-level bridge was started. In the new construction that was completed in 2010, old pillars of Jamarat have been replaced by larger elliptical shaped pillars. The five-level bridge is designed carefully with "Safety First, No Compromise" principle and each level serves Hajjis approaching from different directions. Hajjis approaching the bridge cannot encounter Hajjis coming from any other direction. The flow of pedestrians is unidirectional; Hajjis enter from one side of floor and leave from the other side. The structure is completely free from internal columns to avoid congestion and stampede. Each of the five levels is 950m long with width ranging from 60-97m. The maximum theoretical throughput of the bridge is 3.9 Million Hajjis.

Crowd simulation has become an important tool in design and analysis of complex architecture as there is no test data available that can be used to analyze the conceptual design before construction phase. Also it is not possible to analyze critical parameters after construction because of life threat to human beings. A number of pedestrian simulation software have been developed analyze a conceptual design for critical parameters such as safety, throughput, peak load performance and evacuation strategies. Some of commercial and open source pedestrian simulation software include Legion [4], Simulex [5], Pedestrian Dynamics [6], PedGo [7], Sim Walk [8] and MatSim [9].

A number of simulation studies were performed on proposed conceptual design of Jamarat bridge to evaluate throughput, peak load and safety of Hajjis[10]. The parameters to be studied included shape of Jamarat pillars,

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ingress, waiting time for Hajjis, egress, maximum throughput and evacuation strategies. The shapes studied included circle, and ellipse, and deformed circle. The results of simulations and in-situ analysis proved that elliptical shape of Jamarat pillars results in the most optimal queuing of Hajjis during Ramy.

Rest of the paper is organized as follows. Section 2 highlights related work on simulation studies related to rituals of Hajj, especially for Ramy. The proposed model is detailed in Section 3 along with its agents, inputs, outputs and interaction and decision rules. Details of experimental results are given in Section 4. The paper is concluded and the future directions are highlighted in Section 5.

2. RELATED WORK

The global importance of Hajj for Muslims in the world, gathering of a large number of Hajjis in Hajj and huge stakes in this event have motivated researchers to study Hajj and propose solutions for issues related to various rituals in Hajj. The related work is divided into three sections. A brief discussion on solutions proposed for the ritual of Tawaf is followed by a rigorous review of techniques related to crowd visualization and simulation in Jamarat area. This work can further be divided into tools and techniques proposed for educational purpose to better educate Hajjis regarding Hajj and analysis of architectural design or crowd management.

Tawaf refers to circumambulating the Ka'aba building seven times in a counterclockwise direction. Tawaf can be performed anytime during the whole year and it is mandatory for every Hajji to perform Tawaf in a specified time period. The maximum radius of Mutaf (Tawaf courtyard) is about 48 meters [11] and the tight constraints of a limited space, a large number people, diversity of Hajjis (in terms of age, gender, physique, education, training/experience of Hajj and presence of wheelchairs) and a limited time period make Tawaf an interesting research problem. Sarmady et al. [12] proposed a micro-level movement behavior system for a rule-based modeling of Tawaf to pre-determine pedestrian movement during Tawaf. Al-Haboubiet al. [13] presented a design to minimize congestion around the Ka'aba during the Tawaf ritual by eliminating cross trafficking. Koshaket al. [14] analyzed movement of Hajjiin the Tawaf area using GPS units rather than traditional crowd analysis techniques. Abdelghany et al. [15] simulated Tawaf crowd using a cellular automata approach with features to model dynamic adjustment of Hajji destination and movement direction. Curtis et al. [16] simulated Tawaf crowd using agent based modeling and simulation approach with features to model Hajji's age and gender with a finite state machine and collision avoidance algorithm.

Mulyana and Gunawan [21] developed an agent-based simulation of various rituals of Hajj. The focus of this work is on educating the Hajjis on various rituals of Hajj. Schneider et al. [23] developed a 3D model of Makkah that encompasses all rituals of Hajj. The developed model can be used to analyze any architectural changes in Makkah and as a decision support tool for management authorities. It can also be used as an educational tool to create awareness among Hajjis.

AlGhadi et al. [17] developed a mathematical model for radial/lateral movements and Ramy process at Jamarat bridge. This model was developed for the old Jamarat bridge when Hajjis used to go in the Jamarh ring to collect stones and then returned to the outer side of ring to perform Ramy process. Al-Haboubi[18] proposed to restrict movement of Hajjis to uni-directional lanes of one meter width and restrict the stone throwing zone to 15 meters of radius. This study has, however, some serious limitations including physical dimensions of Hajjis not considered, restricted class of population sample, and delegating Hajjis. Also, the study negates an established principle of crowd psychology of never confining such a large and diverse group of people having different age, background, race and physiques; which may result in serious congestion. The proposed evacuation strategy may also prove very dangerous as the crowd flowing in opposite directions may result in stampede. Koshak [19] simulated movement of groups of Hajjis to and from Mina according to the schedule developed by Saudi Ministry of Hajj. A base map of Mina was developed and a number of layers were developed for features of network traffic, paths of pedestrian movement and geography of Mina and Jamart. The study attempts to support a smooth movement of Hajjis smoother. Andijani et al. [28] developed a simulation model for shuttle buses between Muzdalifah and Arafat. The proposed model is based on spatial and time constraints and attempts to measure travel and evacuation times.

Fayoumi et al. [22] simulated the Ramy process with Steps software tool and analyzed the impact of organizing Hajjis into rows around Jamarat basin. The simulation suggests a linear relationship between perimeter of Jamarat basin and throughput of Ramy process. The authors suggest that overall performance of Ramy process can be increased by 25% by increasing Jamarat basin parameter by 20%.

Khoziumet al. [24] proposed an integrated decision support system to closely monitor and control crowd movements for protection against accidents caused by congestion. The authors propose to use thermal cameras to measure crowd density at critical locations and trigger alarms when density exceeds a certain threshold. The proposed conceptual model, however, needs to be implemented to validate its effectiveness.

An interesting discovery was made by Helbing et al. [20] whose analysis of video footages of crowd stampede in the year 2006 revealed a sudden change in crowd movement from laminar to stop-and-go and then turbulent. This finding has serious implications on all studies of crowd simulation for crowd flows in Hajj that consider the crowd flows to be laminar. Klüpfel [25] used simulation studies in PedGo to emphasize the importance of assumptions used in a simulation study. They focus on the choice of route selection that has a significant impact on the simulation study and stress that simulation parameters must be carefully defined to validate any simulation study.

The most notable work regarding simulation of Ramy is that of Alghadi and Still [10]. In 2003, Saudi Ministry of Public Works and Housing (MPW&H) in cooperation with the Custodian of the two Holy Mosques Institute for Hajj Research, proposed a new 5-level design of the Jamarat area and appointed a committee to evaluate the proposed design for performance, throughput and safety through simulation. Dr. G. Keith Still was appointed by the committee to support in this project. Myriad [29], a multi-scalar modeling tool developed by Still was used for the simulations. A specialized simulation tool, Walker, was also developed for this project. These tools were used to identify any shortcoming in the proposed model that may result in overcrowding and analyze capacity, throughput and performance of the proposed structure. Each of the five levels was tested for sufficient ingress capacity, throwing area, space, passing area and egress. The simulations revealed that the existing circular shape of Jamarah could not be optimized beyond certain limit. A number of other shapes with varying sizes were analyzed. Circle of 16, 20, 30, and 36 meters diameter in 100 meters wide area were tested. The results showed that with increase in diameter, the number of Hajjis queuing for Ramy also increased. Ellipses of size 32m x10m, 32x12, 36x12, 36x14, 40x14, 44x32, 46x30, 48x26, 50x22, 52x18 were also analyzed. Deformed circles and deformed ellipsis of various sizes were also considered. The studies found that an ellipse outperforms all other shapes as regards queuing of Hajjis for Ramy. The developed models, however, do not take into account various sentiments such as anxiety, fear and confusion that play a major role in the movement of Hajjis.

3. PROPOSED MODEL OF THE RAMY PROCESS

Selection of simulation platform is the first design choice. A number of agent-based platforms are available and an excellent comparison of these platforms is presented by Nikolaiand Madey [30].We have modeled the Ramy process at Jamarat in NetLogo [18], a general purpose agent-based modeling environment that can be used to simulate complex systems. NetLogo is used extensively by academic and research communities in a number of domains such as art, psychology, economics, physics, biology, chemistry, mathematics, computer science, sociology, and system dynamics. The basic building blocks of models in NetLogo are turtles, patches, links and observer. The NetLogo world is a two dimensional grid; each square in this grid is called Patch. Agents and their behavior are dependent upon the underlying model.

The model developed for Jamarat can be used to study the effect of various parameters on queuing of Hajjis in Jamarat. These parameters include pace of Hajjis, Jamarat sight angle and distance of Hajjis, Jamarah hitting range and time to perform Ramy. The code of the model is provided under free license so that an interested user can also extend this model to incorporate any specific requirements. Figure 1 presents user interface of the proposed model. A screen shot of a simulation run is shown in Figure 2. In the following, we explain agents in the proposed model, inputs and outputs of the model, and interaction and decision rules followed by the agents.

3.1. Agents

"Hajji" is the main agent in our model. Hajjis enter the Jamarat area, proceed towards the Jamarah, get close enough to the Jamarah to perform Ramy and exit from the Jamarat area after performing the Ramy. We have defined two types of Hajjis namely: Aggressive Hajjis and Considerate Hajjis. Aggressive Hajjis walk at a relatively faster pace, move directly towards the Jamarah and are generally less considerate forother Hajjis. Considerate Hajjis, on the other hand, walk at a slower pace, move away from the crowd and towards the walls. On approaching the Jamarah pillar, they move closer in the hitting range of Jamarah. After performing Ramy, they proceed towards the egress. Jamarah pillar and walls of Jamarat area are also implemented as static agents for visualization purpose.

3.2. Model Inputs and Parameters

The following parameters are used to define a simulation scenario:

- A user can define *total-number-of-Hajjis to create* in a simulation run and the *rate-of-flow-of-Hajjis* in Jamarat area
- *Percentage-of-aggressive-and-considerate-Hajjis* can be defined by the user.

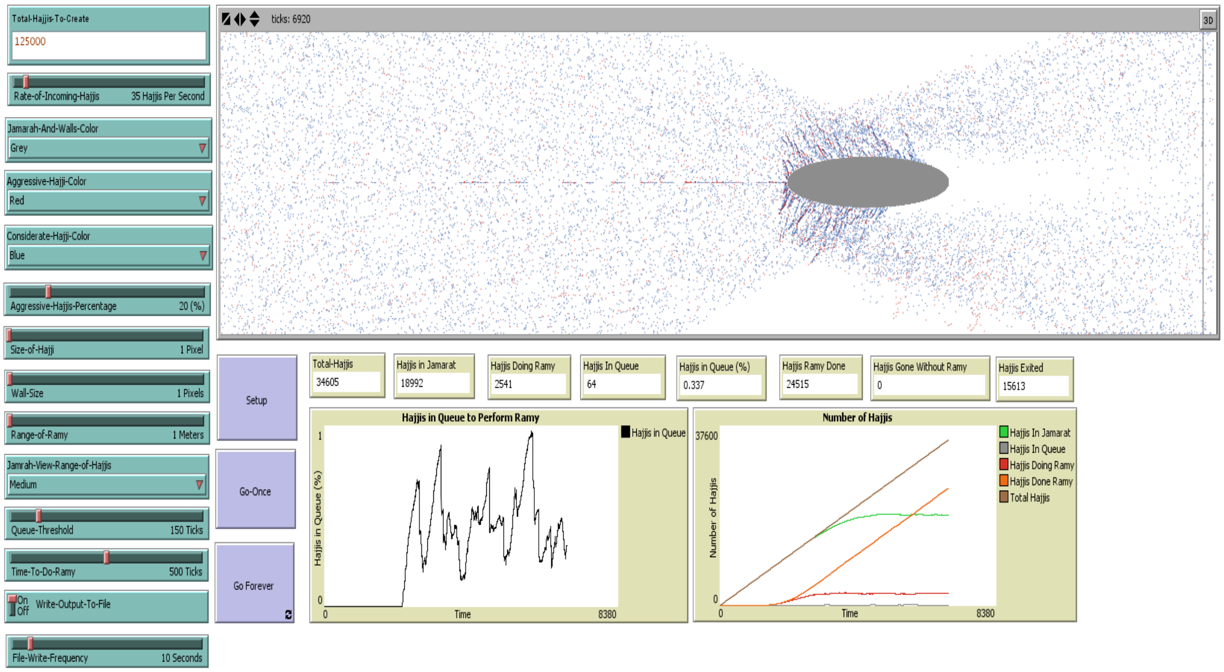

Figure 1: Graphical user interface of the proposed model

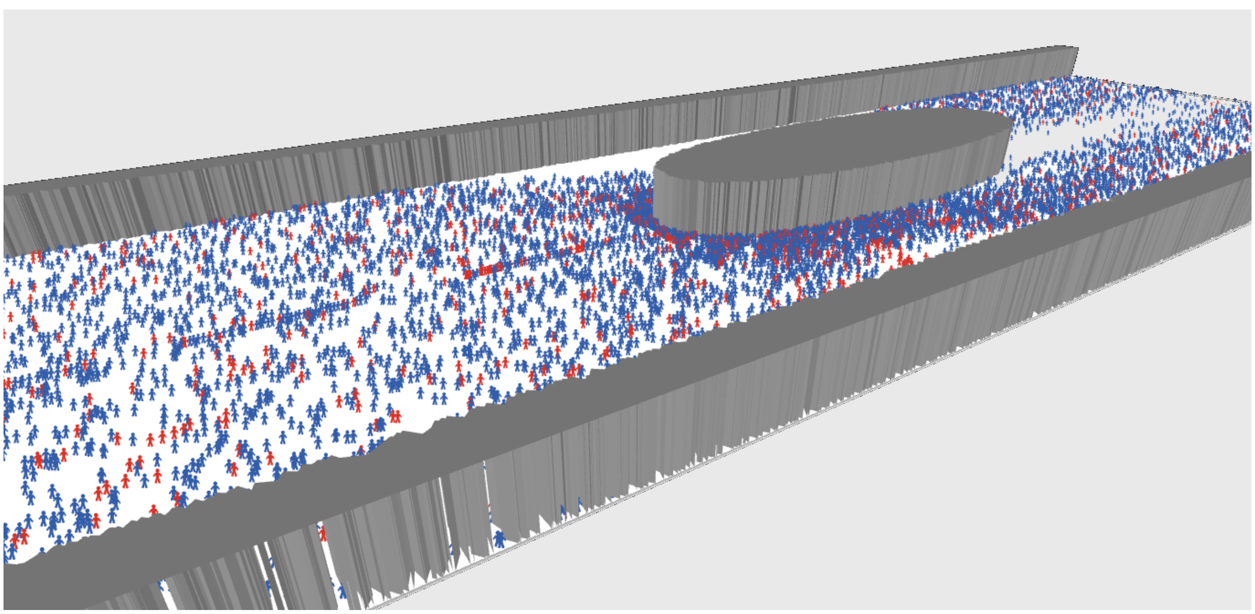

Figure 2: An enlarged 3D view of the simulation

- *Jamarah-view-range* defines angle and distance that is used by considerate Hajjis to change their direction towards Jamarah pillar.
- *Range-of-Ramy* defines hitting range of Jamarah pillar. Typically, Hajjis perform Ram within about 10 meters of distance from Jamarah pillar.
- A Hajji is considered to be static or “In Queue” if s/he is unable to move for a particular period of time. *Queue-threshold* is used to define this period of time. Ticks were used for time measurements instead of seconds because NetLogo does not provide any mechanism to map real time with model time which makes it very hard to compare results of different runs of even the same model. A single iteration in a NetLogo model is completed in one Tick. Generally, 30 Ticks are executed in one second, although it may vary

depending on speed of simulation; taking less than 30 Ticks in one second for more computationally intensive simulations. Hence, setting the value of *Queue Threshold* to 150 means that a Hajji is considered to be "In Queue" if s/he is unable to move for 5-7 seconds.

- *Time-to-do-Ramy* defines the time a Hajji takes to perform Ramy. Typically, a Hajji requires about 30 seconds to perform Ramy but a user can vary this time for analysis purpose. This time duration is also measured in Ticks.
- Additional inputs are defined to define color of Jamarah and walls, colors of aggressive and considerate Hajjis, size of Hajjis, size of walls and Jamarah pillar, an option to save the outputs in a file and the frequency at which the results are written to the file.

3.3. Model Outputs

NetLogo uses monitors to display values of variables or complex statements. The following values are displayed in our model using monitors:

- Total Hajjis created so far
- Hajjis currently present in the Jamarat area
- Hajjis doing Ramy
- Hajjis in queue for Ramy
- Percentage of Hajjis in queue for Ramy
- Hajjis who have performed Ramy
- Hajjis exited from the Jamarat area

Two plots are used to plotvalues of thesevariablesin each Tick. A user may opt to store these values in a comma separated file at regular intervalsfor further analysis.

3.4. Initialization

The SETUP procedure is used to initialize values of variable for the required simulation setup. The pseudo code of the procedure is give below:

```
Procedure SETUP
    Clear all
    Reset timer and ticks
    Initialize global variables to zero
    Setup Jamarat and walls
    Open output file
End
```

3.5. Interaction and decision rules

Generally, in NetLogo models, GO procedure as an entry point of simulation (similar to main function in C or Java language). It is repeatedly executed with each Tick of simulation until the termination condition is met. In our proposed model, GO procedure calls MOVE-HAJJIS procedure to move all Hajjis one step ahead and writes values of required output variables to the output file. When there are no Hajjis left in the Jamarat area, the simulation is stopped and output file is closed.

```
Procedure GO
    ADD-HAJJIS
    If there is at least one Hajjis in the area
    {
        MOVE-HAJJIS
        Write current values of variables to output file
    }
    Else
    {
        Close output file
        Stop
    }
End
```

ADD-HAJJIS procedure checks whether the required number of Hajjis has been created in the model. If not, aggressive and considerate Hajjis are created according to user-defined proportion and inflow rate.

MOVE-HAJJIS procedure is the heart of our model. If a Hajji has reached at the exit of Jamarah, s/he is removed from the model and the corresponding variables are updated. For each Hajji in the model, it checks if s/he can see the Jamarah pillar at user-defined angle and distance. As stated earlier, aggressive Hajjis move straight towards Jamarah while considerate Hajjis initially move towards walls and start moving towards Jamarah from a particular (user-defined) distance and angle. This angle is calculated by Equation 1 as follows.

$$\theta_j \;=\; \tan^{-1}\frac{J_{cy}-H_y}{J_{cx}-H_x}+\delta \qquad \text{(Equation 1)}$$

Where J_{cx}, J_{cy}, H_x and H_y are coordinates of Jamarah pillar and Hajji respectively. Additionally, δ is given by the user to change view range of a Hajji. Similarly, distance towards Jamarah pillar is calculated by Equation 2 as below:

$$D_j \;=\; \sqrt{(J_{cx}-H_x)^2+(J_{cy}-H_y)^2} \qquad \text{(Equation 2)}$$

As view angle directly affects view range, no additive factor is required to change the view range.

When a Hajji “sees” the Jamarah pillar at the required distance and angle, GO-FOR-RAMY procedure is called for that Hajji. Hajjis not doing Ramy MOVE-FORWARD. Finally, Hajjis who have performed Ramy are directed to move outside from the Jamarah pillar.

```
Procedure MOVE-HAJJIS
If a Hajji has reached egress
{
    Increment Hajjis-Exited by 1
    Decrement Hajjis-in-Jamarat by 1
    Remove Hajji from the model
}
If Hajjis is not going for Ramy and has not done Ramy
{
    If Hajjis can see the Jamarah at the required angle and distance
    {
        Set Going-For-Ramy = True
    }
}
Else
{
    GO-FOR-RAMY
}
If Hajji is not doing Ramy { MOVE-FORWARD}
If Hajji has done Ramy but cannot MOVE-FORWARD
{
    If Hajjis is on left of Jamarah pillar{Turn left and MOVE-FORWARD}
    Else {Turn right and MOVE-FORWARD}
}
End
```

MOVE-FORWARD procedure is used to move a Hajji one step in one simulation iteration. A Hajji moves forward one patch in the current heading direction if the patch is not occupied by a Hajji, otherwise Hajji tries to move forward inwards i.e., towards Jamarah pillar. Hence, a Hajji on the left side of Jamarah turns right and vice versa. Note that this movement is opposite to the movement of Hajjis who have done Ramy. After performing Ramy, Hajjis try to move outwards from Jamarah pillar i.e., a Hajji on left side of Jamarah pillar turns left turn and moves forward. NetLogo built-in primitive FORWARD SPEED is used to move a Hajji forward.

```
Procedure MOVE-FORWARD
If there is no Hajji on patch ahead
{
    FORWARD speed
}
Else
```

```
 {
     Save current heading direction
     If Hajji is on left side of Jamarah {Turn Right}
     Else {Turn Left}
     Move forward
     Restore previous heading direction
 }
End
```

The procedure GO-FOR-RAMY checks if a Hajji has not done Ramy and is not in the hitting range of Jamarah pillar and is unable to move then *In-Queue-Ticks* variable is incremented for that Hajji. When *In-Queue-Ticks* variable exceeds *Queue-Threshold* defined by the user, the Hajji is considered to be *In-Queue*. If Hajji is in hitting range of Jamarah pillar, then s/he starts doing Ramy and does not move for *Time-To-Do-Ramy*.

```
Procedure GO-FOR-RAMY
 If Hajji has not Done-Ramy and not CAN-MOVE and is not IN-HITTING-RANGE
 {
     Increment In-Queue-Ticks by 1
     If In-Queue-Ticks > Queue-Tick-Threshold {Set In-Queue= True}
 }
 If Hajji has not Done-Ramy and not CAN-MOVE and is IN-HITTING-RANGE of Jamarah pillar
 {
     Set Doing-Ramy= True
     Set In-Queue= False
     Set In-Queue-Ticks= 0
     Increment Hajjis-Ramy-Done by 1
     Set Done-Ramy= True
 }
End
```

Procedure IN-HITTING-RANGE reports true if there is Jamarah pillar boundary at the specified distance from the current position of Hajji, false otherwise. The PATCH-AT built-in NetLogoprimitive is used for the purpose.

```
Procedure IN-HITTING-RANGE
 If the color of Patch at Range-of-Ramy distance from the Hajji is Jamarah-Color {Report True}
 Else {Report False}
End
```

Similarly CAN-MOVE procedure reports true if there is no Hajji on the next patch, false otherwise.

```
Procedure CAN-MOVE
 If next patch is occupied by a Hajji {Report False}
 Else {Report True}
End
```

4. EXPERIMENTS AND RESULTS

Experiments were performed to analyze the impact of shape of Jamarah pillar on queuing in the Jamarat area. Various shapes of Jamarah pillar were analyzed with different values of simulation parameters i.e., range of Ramy, queue threshold and time to do Ramy. It is worth mentioning here that for the existing elliptical shape of Jamarah tower, the actual measures were used. These measures were taken from GPS visualizer tool[19]. As the existing bridge was designed for a maximum throughput of 125,000 Hajjis per hour per bridge level, the number of Hajjis for all simulation tests was fixed to 125,000. Accordingly, the rate of flow of Hajjis was set to 35 Hajjis per second.

The first run of simulation for the three shapes of Jamarah used 8 meters range of Ramy. Queue threshold was set to 150 ticks and time to do Ramy to 500 ticks. Figure 3 shows results of the simulation. The current elliptical

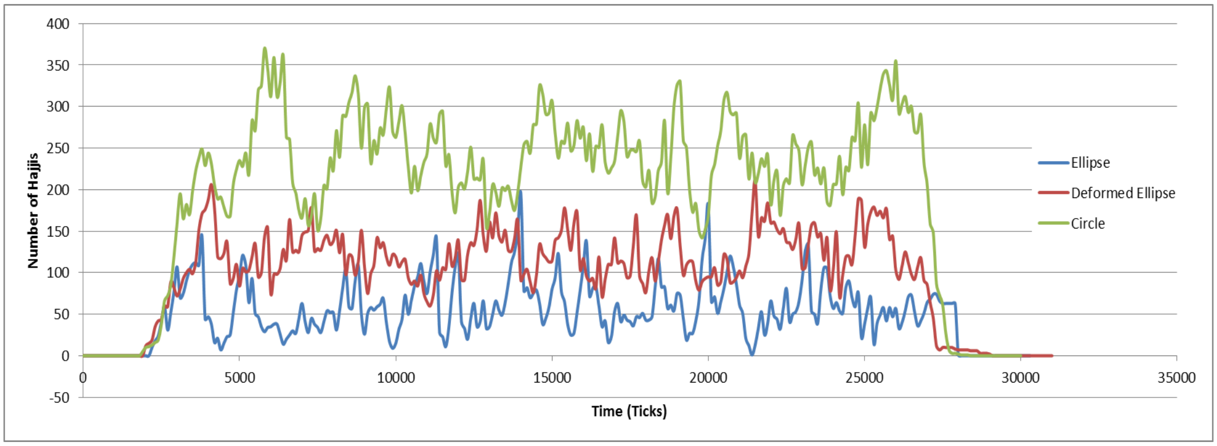

Figure 3: Number of Hajjis in Queue for different shapes of Jamarah pillar for Range of Ramy=8m, Queue threshold =150 ticks and time to do Ramy = 500 ticks

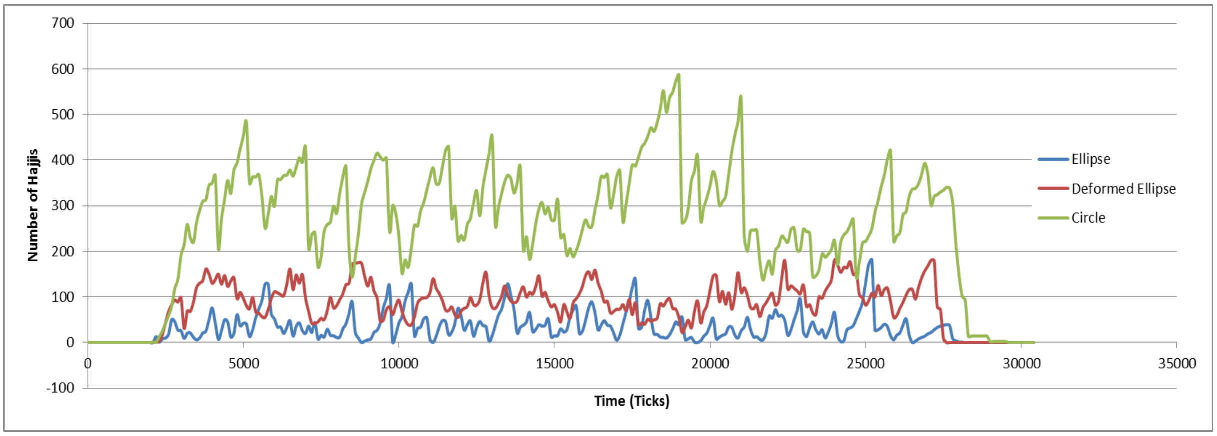

Figure 4: Number of Hajjis in Queue for different shapes of Jamarah pillar for Range of Ramy=10m, Queue threshold =200 ticks and time to do Ramy = 600 ticks

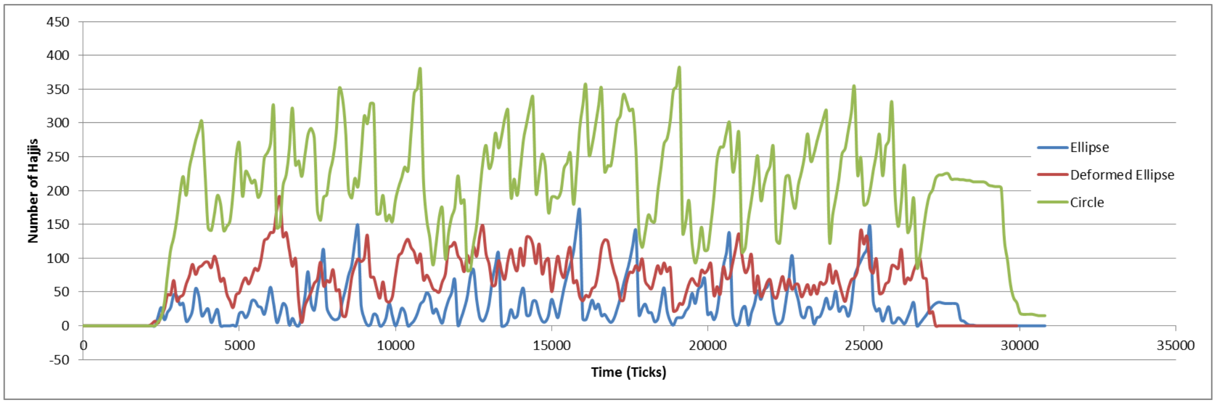

Figure 5: Number of Hajjis in Queue for different shapes of Jamarah pillar for Range of Ramy=10m, Queue threshold =250 ticks and time to do Ramy = 500 ticks

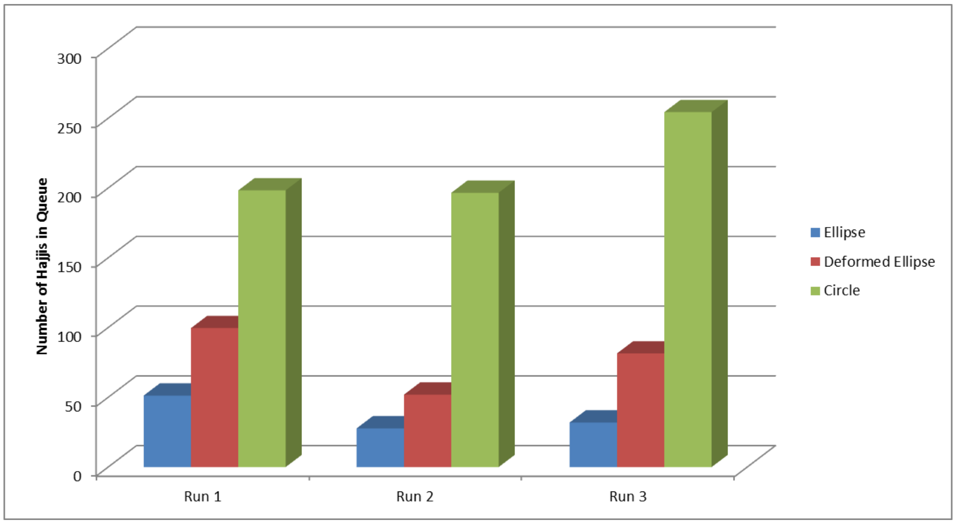

Figure 6:Average number of Hajjis in queue for various shapes in three simulation setups

shape of Jamarah pillar outperforms circle and deformed ellipse shapes. The average number of Hajjis is queue is 48 (0.30%) for ellipse, 97 (0.55%) for deformed ellipse and 198 (1.1%) for circle. The second run of simulation for the three shapes of Jamarah used 10 meters range of Ramy. Queue threshold was set to 200 ticks and time to do Ramy to 600 ticks. Ellipse 32 (0.17%), deformed ellipse 81 (0.45%) and circle 246 (1.42%).

The third run of simulation for the three shapes of Jamarah used 10 meters range of Ramy. Queue threshold was set to 250 ticks and time to do Ramy to 500 ticks. Ellipse 27 (0.16%), deformed ellipse 63 (0.35%) and circle 180 (2.24%).

A comprehensive view in Figure 6 shows overall average number of Hajjis in queue for all simulation runs. It is clear that ellipse outperform the other shapes in all simulation setups. It is also evident that average number of Hajjis in queue has a direct relationship with queue threshold and an inverse relationship with time to do Ramy.

5. CONCLUSION AND FUTURE WORK

We have developed a basic model for Ramy at Jamarat area. The model can be used to analyze effect of various parameters in Ramy such as percentage of aggressive and considerate Hajjis, Jamarah pillar view range of Hajjis, hitting range of Jamarah pillar and time to perform the ritual of Ramy. The experiments performed for various shapes of Jamarah pillar are in conformance with the results achieved by AlGadhi and Still[10]. This model, however, is at a very primitive stage and a number of parameters need to be considered to make it more useful. In the future work, we intend to quantify important sentiments of Hajjis such as fear, anxiety, confusion and directional focus as they play an important role in crowd dynamics. In the current set up, individual Hajjis are considered but generally Hajjis perform Ramy in groups. Each group has a leader and the rest follow. Followers – especially those who are weak, aged or less confident – try to keep a close distance with the leader.Hence, consideration of groups is another important parameter for this model. It is also noted that behavior of various Hajjis varies significantly based on their demography, education level, experience of doing Hajj, gender and age etc. Another important consideration would be to use advanced crowd dynamics and collision avoidance strategy used by Hajjis. Currently, we have used very basic mechanism for movement of Hajjis. If the next patch is already occupied then a Hajji turns towards the Jamarah pillar before performing Ramy and away from it after s/he has performed Ramy. A more realistic representation of movement of a Hajji is required for collision/crowd avoidance and one's search for the most suitable place to perform Ramy. Another limitation of the current model is that only one Jamarah pillar is modeled. A more comprehensive model needs to be developed considering all three Jamarat pillars as well as all five levels of Jamarat bridge. The last but the most important improvement is speed optimization of the model. Despite developing a very simple model and having descent hardware to run this model, we had to be content with simple heuristics instead of more sophisticated techniques requiring complex computations. An example of this compromise is the use of PATCH-AT primitive to give "vision" to Hajjis. While PATCH-AT enables Hajjis to "see" only one patch at a particular distance, IN-CONE is a more realistic choice as it enables Hajjis to "see" agents (patches, Hajjis and walls) in a cone which is the way human beings see. However, using IN-CONE for as small as five degrees of angle and 10 pixels ahead slowed down the model to an extent that a single model Tick required many seconds to execute. Currently, we have used patch size of one pixel. In our future work, we may use a larger patch size to improve the simulation speed. The trade-off in case of a larger patch size, however, is that it will result in relatively rougher edges of Jamarat pillar walls.

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