Systematic Crowd Mobility Management to Avoid Catastrophic Disasters of Human Stampedes: The Case of Mina Hajj

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Abstract: Every year, the Holy city of Makkah hosts more than two million Muslims for the pilgrimage 'Hajj'. During this event, a set of activities should be done by pilgrims. One of the rituals performed is throwing stones in al-Jamarat area of Mina at pillars target. The throwing Jamarat is a paradigm of stoning the devil, as done by the prophet Abraham. All pilgrims must reach the site at different times in specific hours of particular days. However, this stoning ritual represents the most bottleneck ceremony where the area becomes packed at routes and around pillars structure. The problem is that, unfortunately, humans cannot be controlled while they are in a crowd. That takes this place a high safety hazard by increasing accidents' probably which cause death of many Muslims last few years. Inspired from this event, this paper presents a new human mobility models which simulates stoning in Hajj by adopting a new design to solve the safety problems. This suggests control huge crowds by conducting the relationship between the Jamarat basin, pilgrims, stoning performance, and the impact of organizing the pilgrims in three rows around the Jamarat basin. This experiment estimate the throwing time at each pillar in order to manage the temporal and spatial human movement inside the Jamarat area. The simulation outcomes encourage adopting the new design to prevent crowd panic and disasters.

1 INTRODUCTION

Up to now, mobility modeling field cognizes a lot of interests and research advancements. That especially ever knows an important expanding of human or sociability based mobility models. From the beginning of 1990, biologists, physicists, and other groups of researchers looked into human and animal movement patterns. Their research detected that their motions are heavily influenced by various factors like food location, foraging, habitat, and tendency to create groups as herds or communities, for instance, group of soldiers or rescue workers. That can be applied to diverse applications of Pocket Switched Networks (PSN) (Trifunovic et al., 2017). Numerous mobility patterns have also been suggested inspired by sociology and social network. Therefore, There are based on the argument that Humans have tendency to socialize where they are governed by social aspects and the nature of social structure of the belonging community. Moreover, people are confined to their own social group and seldom move outside it. For example; during their days, people are in office, the evening in a pub or coffee shop and return home at night. Hence, human mobility is more complex than animals that stills till now under research.

The pilgrimage to Makkah at Saudi Arabia is one of the five needed pillars of Islam. Muslims are charged for this duty at least one time in their lifetime, if they can financially and physically afford it. Over a fixed five days, the holy Makkah hosts around 2 million people. A population of international Muslims that annually comes from more than 150 countries from all the world. This event represents the largest mass gathering of all the globe. Recently, the number of pilgrims has exponentially multiplied, as shown in Figure 1. That makes the Hajj a huge logistic issue

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repeated each year at the same time, at the same place with more and more of hosted pilgrims.

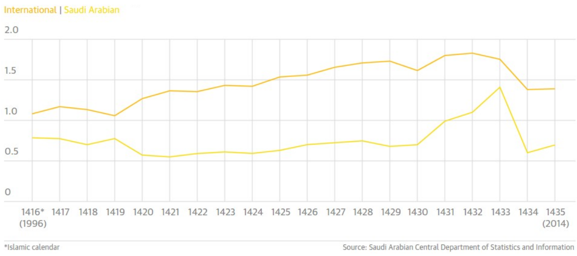


Figure 1: Nationality of pilgrims at the Hajj by millions.

One of the focal points of pilgrimage is 'Stoning of the Devil' at the Jamaraat Bridge in Mina. That comes few miles of Makkah and known as the 'Tent City', as depicted in Figure 2.

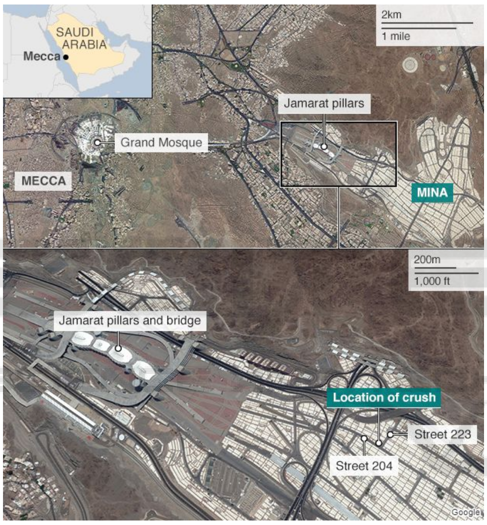


Figure 2: The tent city (Mina) location.

This area is a pedestrian zone that covers about 20 km^2 and from which pilgrims throw small stones at the three Jamaraat pillars. During three successive days, pilgrims throw at a target and hit it seven times in sequence, starting with the smallest and finish with the largest. However, the stoning ritual is conceived the most bottleneck dangerous and unsafe process by dint of cramped spaces, tight scheduling, and large crowds.

Figure 3: Pedestrians' flow in Jamarat plaza at Hajj.

Therefore, the pilgrimage has previously witnessed several tragic stampedes and catastrophic crowd disasters in the past. Basing on the civil defense statement, the last scamper was happened Thursday 24 September 2015 nearly at 09:00 am (Mecca time) towards the Jamraat Bridge at the intersection between 223 and 204 streets, as presented in Figure 2. This disastrous accident is looked as the deadliest stampede of the 21st century with 2110 deaths and about 863 were injured, as dramatically shown in Figure 4.

Indeed, disasters are far from rare in Mecca, as displayed in Table 1. There occur trampled of deaths and suffocated people which are usually killed in squeeze crushes. This large crowd necessitates decisive control with the notably increase in the number of pilgrims. The need for more researches that suggests an efficient and new perfections for Hajj rituals primarily in stoning. Inspired from all previous tragic stampedes, this current paper proposes a new human mobility model which manage and control movement flows of pedestrians during the three consecutive days

Table 1: Tragic stampedes during Hajj.

Date	What happened where	Deaths
24 September 2015	Stampede at junction of streets 204 & 223 in Mina	2110
12 January 2006	Stampede at Jamarat Bridge in Mina	364
1 February 2004	27-minutes stampede during Jamarat stoning	251
11 February 2003	Stampede at Jamarat in Mina	14
5 March 2001	Stampede at Jamarat in Mina	35
9 April 1998	Stampede/overpass fall-off at Jamarat Mina	118
15 April 1997	Fire fuelled by high winds in tent city, Mina	343
23 May 1994	Stampede at Jamarat in Mina	270
2 July 1990	Stampede/suffocation in tunnel leading to Haram	1426
31 July 1987	Security forces break up anti-US demo by Iranian Hajis	402

Figure 4: Tragic human stampedes.

at Mina. This pattern prevents crows and panic stamples while stoning the devil by taking into consideration number of predistians within a specific time period and limited space location of the tent city.

The remaining part of the paper is organized as follows. Section 2 tackles some related works of some human mobility models previously suggested for different and under diverse constraints. Section 3 highlights the mobility features, the main motivation, the detailed process and properties of the proposed human mobility model. Section 4 discusses the obtained pattern, and finally the conclusion.

2 RELATED WORKS

Human motion management research field knows many human mobility models that have been proposed till now. These patterns are primary applied to extract and recognize human whereabouts for mobile networks. Among these patterns, we propose a brief description of the most used at network simulations:

In (Jeon et al., 2017), the authors present the Community-based mobility model (CMM) where the motion of mobile nodes are based on socialization behavior and human decision. These devices are carried by Humans which by nature they tend to gather and establish communities. All movements are in groups and between groups. This mobility heavily depends on the social relationships among devices. An Interaction matrix is used to model structure of connexions between people carrying devices. The strength of interaction between any two nodes i and j are represented by an element m(i,j). A connectivity matrix (C) is picked up where if and only if m(i,j) is bigger than a specific threshold (often 0.25) leads to C(i,j)=1 and if it is less than 0.25, the c(i,j)=0. From this matrix, we can detect structures of relationships into a community via algorithms which already proposed Girvan and Newman (Girvan and Newman, 2001). Communities are initially located within a definite place or a square inside a grid. Moreover, a given device may change its current position after a time-interval t. And, the next waypoint (destination) mainly relies on the location of other nodes with a strong social connectivity. Furthermore, every node is found in various communities at different times. That reflects real-life activity where a person is at different locations within a day. For instance, a person is mostly at the office from morning till afternoon, at the coffee shop in the evening with friends, and at home at night with family. So, a person changes communities belonging within a day at different locations and at different times.

In (Ibadah et al., 2018), Self-Similar Least Action Walk (SLAW) has been introduced which combines the main features of human motion, as: least-action trip planning (LATP), truncated power-law inter-contact times, heavy-tail flight and pause-time distribution, self-similar dispersal of destinations, and heterogeneously bounded mobility areas of individuals.

The authors analyze major parts of Dartmouth WLAN traces to suggest Time-Variant Community Model (TVCM). They recognize two main mobility features. They differentiated skewed location visiting preferences and periodical re-appearance at the same position. Skewed location visiting preferences demonstrates how one node can spend its time at diverse places. However, periodical re-appearance at the same position displays the period in which a device appears at the same place again. According to traces, a node spends at a specific AP an average of 65% of its online time and more than 95% at few than 5 APs (Batabyal and Bhaumik, 2015).

In (Wang et al., 2015), Sociological Orbit aware Location Approximation and Routing (SOLAR) considers repeated visits of a given node to a set of locations. It is noticed that people routinely located at a specific place for an appointed period of their daily lives. The authors call these locations as ”hubs”. Thus, the ”mobility profile” of a person is the repetition of inter-hub motion which is in generally periodic or orbital. In SOLAR, the whole experimental area is divided into several hubs. Every individual randomly selects a set of hubs which it can visit, as a hub-list. Based on the ”hub-stay time”, each node remains or travel inside the hub. And then, it moves to the next hub. The intra-hub motion can adopt random walk or random waypoint and the inter-hub is linear.

In (Mei and Stefa, 2009), Small World in Motion (SWIM) is presented where its concept is based on two human mobility facts; 1. Human tend to mostly visit some popular places and frequently near to their home. And, they seldom visit far places and less popular. And, 2. Human spend less time at less popular places and most time at the most popular. However,

Table 2: Qualitative features of the human mobility models,
Y: Yes, N: No, A: Ambiguous.

Human mobility models	**Realistic**	**Scalable**	**Possibility of a mathematical representation**	**Uses geographic map**	**Possibility of simulation**
MhMM	Y	Y	Y	Y	Y
CMM	Y	Y	Y	Y	Y
SLAW	Y	Y	N	Y	Y
TVCM	N	Y	N	N	Y
SOLAR	N	Y	A	N	Y
SWIM	N	Y	N	N	Y

a home location is assigned to each node. And also, the whole area is partitioned to a number of destination landmarks which define a weight inversely proportional to the distance between the home location and the destination and proportional to destination's popularity. When a new waypoint is selected by a node, it moves with a constant speed towards this destination. Once a node visits a landmark, its popularity is continuously updated according to present nodes at the same time. When a specific node reaches the targeted location, it waits there for some time and then it selects a new destination.

The Table 2 shows the qualitative features of the previous discussed models. All the proposed human mobility models are often inspired from sociological movements as for social networks. There are based on the supposition of depending on their nature of social communities. In this paper, we present a human mobility model which is related to Jamarat bridge to manage movement crowds of pilgrims during the stoning the devil at the Hajj. The main features and motivation is presented and analyzed in the next section.

3 PROPOSED PATTERN: MINA HUMAN MOBILITY MODEL (MhMM)

3.1 Problem Definition and Analysis

Panic stampede is one of the most dramatic collective attitudes that often causes to the death of people who are trampled down or crushed by others. The diverse collective incident observed in pedestrian crowds have currently catched the interest of a huge number of scientists. The real-life implementation revealed that mostly of the years, some pilgrims die due to the congestion on throwing the stones (rami aljamrat). Some communicated statistics are as follow:

- More than two million of pilgrims per year;
- 20% of pilgrims delegate other pilgrims to do "rami" instead of them;
- Bridge length is about 600 m;
- Bridge width is about 40 m;
- Number of jamrat is three;
- The distances between the three jamrat are respectively 150 m and 190 m;
- According to religion fixed instructions, the locations of the three jamrats cannot be shifted.

Figure 5: The three circles of jamarat.

This paper proposes an improved concept of management and control the pedestrian flow movements at the Jamarat area in the regular annual pilgrimage to Hajj season. More than two million of pilgrims every year perform their rituals in the midst of a narrow space and limited time constraint.

3.2 MhMM Concepts

We usually move in our real life depending on geographic restrictions. That makes our mobility behaviors primarily related to obstacles coordinates. Moreover, with a huge number of pedestrians in the same location, the motion management becomes trickier. That necessitates a deeper analysis to overcome unexpected tragic stampedes and catastrophic crowd disasters. In this case, we need a flexible mobility management which will based on real requirements, as the area size, number of mobile nodes, specific coordinates of zones, needful time, and traveled distance.

All these mobility features must be related to a realistic conduct of mobile nodes with taking into consideration the historical and spatial dependencies inside the simulation field. That later allows accurate trajectories to travel from one zone to another with the most convenient parameters. The proposed model can modulate pilgrims motions within a specific time period and limited space location of the tent city. Therefore, in this part, we attempt to itemize the various steps of the new human mobility model entitled Mina Human Mobility Model (MhMM).

Indeed, each pilgrim is considered as a mobile node which is identified by a node number, initial coordinates, a speed from a range of 1.5m/s to 5.5m/s, is attributed to reflect all pedestrians class (fat, tall, adult, child and old). These nodes are two types: 20% of total mobile nodes are fixed at zone 1. However, 80% can move to the other zones by selecting a new position to enter in zone 2 in order to start a movement round. These mobile nodes must travel three rotations where each one contains five movement decisions to return to the departure position. The same process must be repeated three times with a bit difference; the small jamarrat at first tour then the median at the second afterwards the biggest as the third. Besides that, one day must be between two consecutive tours namely 86400 seconds is added to the arrival instant of the previous one. The resulted outcomes ensue a coherent human mobility model. That owns the tractability of all nodes which their motion features, as node identifier, coordinates, speed and time.

3.3 MhMM Implementation Process

Based on previous features, the implementation of Mina pattern follows five main steps, as displayed by the diagram process of Figure 6. The aforementioned steps are detailed as follows:

Step 1: Mina Field Partition

The creation of Mina area represents the first step to generate Mina human mobility model. This field is spread on approximately $20km^2$. In this part, we suggest a new design to improve stoning process from the tent city to Jamarrat bridges, as shaped in Figure 7. This area is split to several zones:

- Zone 1 represents the lodging region for mobile node which reflect the tent area. They must start and return to this zone after the stoning process.
- Zone 2 is the passage between zones 1 and 3.
- Zone 3 depicts the stoning region with the three Jamarat bridges that each mobile pilgrims must reach one bridge at each full round.
- Zone 4 return path to zone 1 after stoning at zone 3.

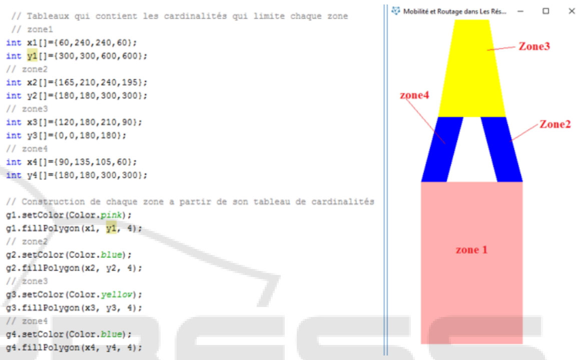


Figure 7: Mina field partition.

This step is generated once time during all deployment time. The detailed coordinates of the resulted design will be used by all mobile nodes with the aim to correctly move according to the attributed geographic restrictions inside this area.

Step 2: Initial Spatial Node Distribution

- Before start moving, we uniformly distribute total number of pilgrims within the first zone. This procedure allows each mobile node to own a spatial location (xi, yi) that represents its lodging position, as depicted in Figure 8.

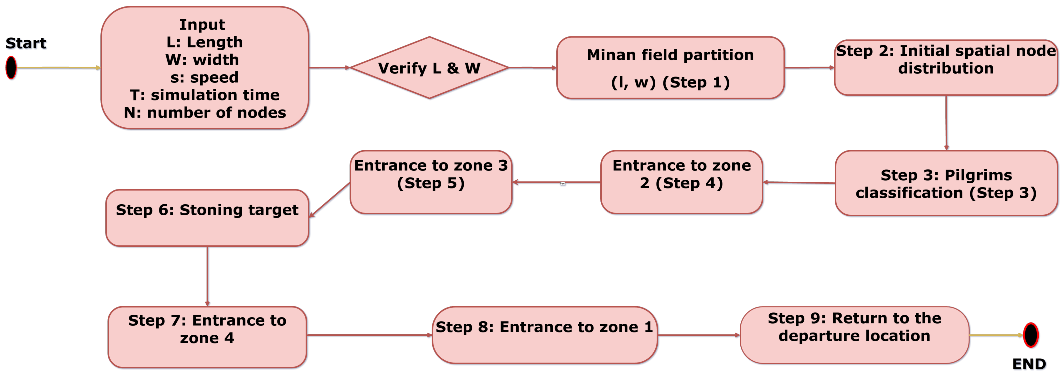


Figure 6: Implementation process of Mina human mobility model (MhMM).

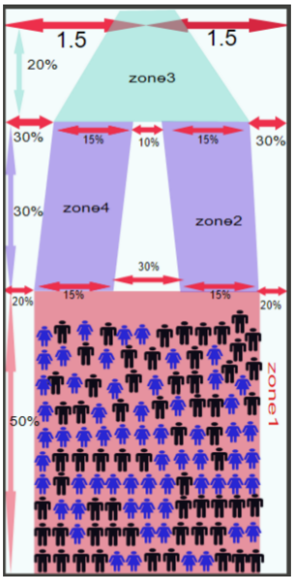


Figure 8: Initial spatial human distribution.

Step 3: Pilgrims Classification

- Due to onerous Hajj activities, Islam allows only at this ritual to delegate another pilgrim which is physically capable to throw stones of old people, sick, or pregnant; for instance. This category is estimated as nearby 20% which still fixed during all three stoning days at zone 1. The other 80% nodes are marked as mobile where they must access respectively to other zones (2,3, and 4).

Step 4: Entrance to Zone 2

- In order to start moving; at this step, the mobile node must own an entrance point to the second zone (x2, y2). These coordinates will be selected based on the Mina field partition. According to the first step, the x2 will be randomly selected between [240, 195] while the y2 will be 300.

- Meanwhile, an assigned speed s(i[n]) must be chosen from a range of [1.5m/s, 5.5 m/s].

- Then; to render this model more realistic, it must respect motion laws where $t = d/s$. The distance D(z1,z2) between the departure point and the entrance position will be calculated based on the Pythagorean theorem. That allows to deduce the time needed t[z1, z2] to travel this calculated distance where **T = D(z1,z2) / s(i[n])**.

Step 5: Entrance to Zone 3

- The same process of Step 3 will be done. The node selects an entrance point to the third zone. The (x3, y3) will be respectively between [120,180] and [0,180]. The distance must be calculated to result in the occupied time t[z2, z3] between (x2, y2) and (x3, y3). This time will be addition to t[z1, z2] to own the current T5 with **T5 = t[z1, z2] + t[z2, z3]**.

Step 6: Stoning Target

- This step makes the dissimilarity for the proposed model. Three different stoning targets are available, the small, the medium and the biggest. Three cycles must be done for each target at three successive days.

- For the first turn, the targeted point will be the small bridge Sb(xs, ys). So, we must result the distance traveled from (x3, y3) to (xs, ys). Then, the recorded time T6 which will be added to last T5: **T6 = (t[z1, z2] + t[z2, z3]) + t[z3, zS1]**

- The same process will be repeated for the two other targets; medium and biggest with two other independent turns.

Step 7: Entrance to Zone 4

- As the Step 5, we must select an entrance position to zone 4 before reaching the stoning target. The (x4, y4) will be respectively between [90,135] and [180,300]. The distance must be calculated to result in the occupied time t[z3, z4] between the stoning position and (x4, y4). This time will be addition to last T6 to own the current T7 which equals to **T6 + t[z3, zS1]**

Step 8: Entrance to Zone 1

- As the Step 5, we must choose an entrance position to zone 1 before reaching the departure location. The (x41, y41) will be respectively between [105,60] and [180,300]. The distance must be calculated to result in the occupied time T8[z4, z41] between (x4, y4) and (x41, y41). This time will be additionned to last T7 to own the current T8.

T8 = T7 + t[z4, z41]

Step 9: Return to the Departure Location

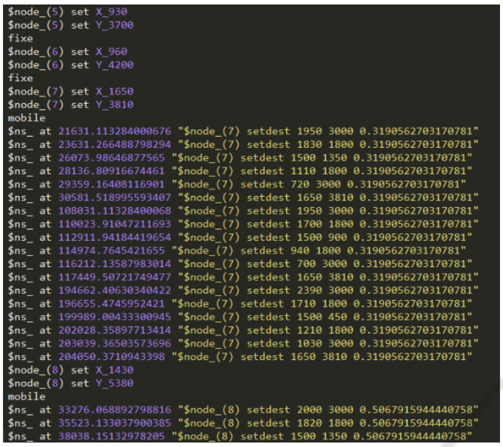
- That represents the last movement decision for each cycle. After several travels, each mobile node must return to its departure location (x1,y1). The distance must be calculated to result in the occupied time t[z41, z1] between the (x41, y41) and (x1, y1). This time will be additionned to last T6 to own the current T9 where **T9 = T8 + t[z41, z1]**

From all these steps are recorded to result in a coherent and realistic synthetic mobility model. Mina human MM saves for each node three different cycles, with the difference at ”Step 6”. These movement decisions represent all detailed steps of stoning during three consecutive days.

4 RESULTS AND DISCUSSION

4.1 Mina Human MM Interpretation

The Mina human MM outputs are saved that record all movement details that contain pertinent information of mobile nodes at each independent step, as the departure position, the identifier of pilgrims, motion duration, speed changing, and so on. This information is related each other to result in a coherent mobility pattern from the initial distribution to pilgrims arrivals. An example of Mina human MM are shown in Figure 9.



```
$node_(5) set X_930
$node_(5) set Y_3700
fixe
$node_(6) set X_960
$node_(6) set Y_4200
fixe
$node_(7) set X_1650
$node_(7) set Y_3810
mobile
$ns_ at 21631.113284000676 "$node_(7) setdest 1950 3000 0.3190562703170781"
$ns_ at 23631.266488798294 "$node_(7) setdest 1830 1800 0.3190562703170781"
$ns_ at 26073.98646877565 "$node_(7) setdest 1500 1350 0.3190562703170781"
$ns_ at 28136.80916674461 "$node_(7) setdest 1110 1800 0.3190562703170781"
$ns_ at 29359.16408116901 "$node_(7) setdest 720 3000 0.3190562703170781"
$ns_ at 30581.518995593407 "$node_(7) setdest 1650 3810 0.3190562703170781"
$ns_ at 108031.11328400068 "$node_(7) setdest 1950 3000 0.3190562703170781"
$ns_ at 110023.91047211693 "$node_(7) setdest 1700 1800 0.3190562703170781"
$ns_ at 112911.94184419654 "$node_(7) setdest 1500 900 0.3190562703170781"
$ns_ at 114974.7645421655 "$node_(7) setdest 940 1800 0.3190562703170781"
$ns_ at 116212.13587983014 "$node_(7) setdest 700 3000 0.3190562703170781"
$ns_ at 117449.50721749477 "$node_(7) setdest 1650 3810 0.3190562703170781"
$ns_ at 194662.40630340422 "$node_(7) setdest 2390 3000 0.3190562703170781"
$ns_ at 196655.4745952421 "$node_(7) setdest 1710 1800 0.3190562703170781"
$ns_ at 199989.00433300945 "$node_(7) setdest 1500 450 0.3190562703170781"
$ns_ at 202028.35897713414 "$node_(7) setdest 1210 1800 0.3190562703170781"
$ns_ at 203039.36503573696 "$node_(7) setdest 1030 3000 0.3190562703170781"
$ns_ at 204050.3710943398 "$node_(7) setdest 1650 3810 0.3190562703170781"
$node_(8) set X_1430
$node_(8) set Y_5380
mobile
$ns_ at 33276.068892798816 "$node_(8) setdest 2000 3000 0.506791594440758"
$ns_ at 35523.133037900385 "$node_(8) setdest 1820 1800 0.506791594440758"
$ns_ at 38038.15132978205 "$node_(8) setdest 1500 1350 0.506791594440758"
```

Figure 9: Mina human mobility model generation.

From this capture, we deduce some mobility decisions, as:

- The mobile nodes are stable or mobile, as the real-life pilgrims classification (Step 3).
- For fixed person, assigned coordinates (X, Y) are selected at the initial spatial distribution (Step 2), as defined for nodes 5 and 6 (930, 3700), (960, 4200) respectively.
- For mobile person as for nodes 7 and 8. A set of mobility parameters are generated to record all nodes positions during the stoning the devil.
- Each line displays: the time, node identifier, X-position, Y-position and the selected human speed from a range (Step 4).
- Several mobility transitions are accomplished to reach the intended destination. The last line of each mobile node displays coordinates of the last location which must be the same with the first position before moving (Step 2).
- Each mobile pilgrim own 18 mobility decisions for the three rounds.

4.2 MhMM Features

The human mobility pattern suggested in this paper owns a set of important features which govern the whole adopted motion strategy. From all the above-mentioned steps, we deduce that Mina human MM is typified by the following features:

- Mina human MM considers the physical laws of motion by taking into consideration the relation between distance, time, and speed (Step 4). That makes this model more realistic.
- It is a time-dependent mobility model: the current time mainly relies on previous time instants, i.e., basically ($t = d/s$) (Step 5).
- It can be considered a direction-history based model. It moves according to the last location. So, it is a spatially dependent mobility model (Step 4).
- The return time and visiting frequency are probabilistically distributed, mainly in relation to the resulting trajectory (Steps 2 and 4).
- At the initial stage, it has a spatial distribution only in zone 1. In the subsequent stages, the resulting trajectory must be constituted only by authorized zones without any walls or restricted fields, as shown by Figure 7 (Step 1). This fact leads a realistic movement behavior that seems like that in daily-life.

The most important movement features of the Mina human MM compared to other human mobility models are highlighted in Table 3. The meaning of the letters is as follows. *C: Constant, UD: Uniformly Distributed, HB: History Based, PD: Probabilistically Distributed, PL: Truncated Power-law, P: Periodic, UD: Uniformly Distributed, NA: Not Applicable*.

We conclude that the Mina human MM takes into consideration a set of realistic movement features to reflect a real human mobility model. It abides by the spatial context with several geographic constraints (Step 1). Mina human MM permits a flexible motion even if in a limited field, that can be modulated with diverse constraints. Based on the resulted pattern, pilgrims can move with the most convient trajectory with crush preventing (Step 5). That solves the simple random process of stoning the devil. It permits an organized motion which further will be adaptative according to pilgrims flow while moving. It exactly reflects a movement with memory which is mainly inspired from human motion in real-life. It results in a flexible and adaptative mobility model which operate in narrow areas, even when diverse mobility requirements are considered.

Thanks to its logical process, its conception, the consideration of real-life movements. These parameters allow the proposed model more efficient and suitable even when diverse mobility constraints are presence.

Table 3: Movement features comparison: MhMM vs. other human mobility models.

Mobility models	**Speed**	**Direction**	**Acceleration /Deceleration**	**Pause Time**	**Flight Length**	**Return time and Visiting frequency**
MhMM	C	HB	C	C/UD	C	PD
CMM	NA	PD	NA	C	NA	P
SLAW	NA	PD on set destinations	NA	TPL	TPL	P
TVCM	NA	PD	NA	C	NA	P
SWIM	NA	UD on set of locations	NA	C/UD	NA	P

5 CONCLUSION

It is important to emulate a real life scenario using a mobility model. During time, the subject of mobility modeling have grown where researchers analyze and suggest new mobility patterns that imitate real life mobility. The aforementioned factors motivated us to propose a flexible human mobility model which is adaptative with the pedestrian's flow inside the Jamarats building. This study suggests multi-solutions to solve the tragic stampedes and catastrophic crowd disasters using a simulation program. That uniformly manage crows by taking into considerations all impacted factors; as the temporal dependencies of previous movement timing, the spatial dependencies of the current position foremost depends on the last location. Meanwhile, geographic restrictions inside the stoning area are considered. Mina human MM acquires strengths from these realistic combinations. The benefits of this study encourage adopting this solution. As future works, the Ministry of Municipal and Rural Affairs in Saudi Arabia must adopt this scheduling program to register pilgrims to get a timetable and an assigned route to distribute them uniformly in the different Jamarat building levels. Awareness and guidance for pilgrims are embedded.

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