# Crowd Movement Analysis in Al-Masjed Al-Nabawy using Modelling and Simulation

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**Abstract**

Crowd simulations have been always an essential tool, which help developing and understanding of crowd risks and safety for many of the world's largest events. Regulating the access to Al-Masjed Al-Nabawy is a complex crowd dynamics analysis problem that require special attention. At the heart of the old mosque is Rawdah. All visitors, attempt to pray in Rawdah. Entrance into Rawdah is not always possible as the tiny area can accommodate only a few hundred people. In addition, visitors want to come to the Ziara Place, where they visit the Prophet's grave.

Every day, many hundred thousand of visitors are keen to visit the Prophet and pray in Rawdah.

Computer simulation can be utilized as an important research tool in understanding the complexity of crowd dynamics across such a wide space. Simulating crowds' behavior in such large-scale and complex environment presents a variety of challenges in representing the interrelated processes that characterize real-world interaction.

This paper focuses specifically on the problem of simulating the dynamics of large, dense crowd in Rawdah and Ziara Place. Such crowd exhibit a low interpersonal distance and a corresponding loss of individual freedom of motion. Different simulating models are presented where concurrent groups of simulated agents interact in a modeled environment of the Al-Masjed Al-Nabawy with potential to enable direct acquisition of statistics and indications at levels of detail and accuracy. A series of simulation scenarios are carried out to provide an assessment of the effectiveness of existing systems. Moreover, it can also

contribute in proposing alternatives systems, as well as the possibility of developing indicators and readings to support decision makers.

## 1. Introduction

Crowd simulation systems have been always essential tools that help in developing and understanding of crowd risks. A wide range of crowd simulation systems have been developed and applied to crowd safety for many of the world's largest events over the past decades [1,2].

Methods of assessing crowd density and understanding of the rates at which spaces can fill is vital to avoid dangerous overcrowding. In order to do that, basic information about the space that moving crowd occupies, the rates at which crowds can move, and the rates at which spaces can fill are needed [3]. Crowd simulation systems enable us to experiment with a wide range of behavioral assumptions. Experimentations with crowds using a computer-generated environment can be conducted in a way that is not possible in real time, to get understanding of the interactions between crowds and their environment [4].

Using crowd simulations enable us to understand how risks develop into incidents and how incidents can escalate into disasters. However, simulation techniques have been expensive and time consuming. They utilize mathematical models, which describe the crowd dynamics in addition to the way individuals behave in a range of situations [5,6]. A simulation process is limited by the assumptions of the mathematical model. A simulation process would not behave properly if built in an incorrect or unsuitable set of assumptions.

An important feature of crowd density and risk assessment is to determine which areas within the space will be of high density and which areas will be of lower density, and also to determine which areas are going to be standing and static, and which areas are going to be dynamic. For example, entry and exit gates would be predominately of higher density during ingress and egress, but low density at other times. Occasionally, there may not be time to react between the crowd entering the space and the space becoming too crowded. Therefore, real time monitoring and managing crowd flow and crowd density is essential for crowd safety.

Reviewing crowd accidents from around the world, as an example the accidents in [7], shows that deficient planning before events and unsatisfactory risk management during events are the common causes to major incidents and are the key points of failure.

Many research have been conducted to study the services presented in Al-Masjed Al-Nabawy [1,2,8,9]. Events, like visiting the Prophet's mosque at peak times or praying in

Rawdah, require a significant amount of planning. This process engages a wide range of organizers, such as the emergency services, local authorities, and security authorities. During such special events, careful review of the risk analysis is critical; any risks missed during the planning process must be identified. If planning phase neglects risk assessment, risks may be realized during the operational phase of the event. Computer simulation can be utilized as an important tool in understanding the complexity of crowd dynamics across Al-Masjed Al- Nabawy wide space. Simulating crowds' behavior in such large-scale and complex environment presents a variety of challenges in representing the interrelated processes that characterize real-world interaction.

Crowd risk analysis should include the necessary examination of spaces for both static (standing) and dynamic (moving) crowds. These are spaces such as queuing systems, entry points, exit points, emergency access, etc. There also needs to have crowd monitoring and continual risk assessment during the operational phase of the event, for example, assessment of crowd flow rates for congestion during queuing, at entry points, congestion in critical locations, and whether the system is performing as planned.

This paper focuses on the problem of simulating the dynamics of large, dense crowds in Rawdah and Ziara Place. Such crowds exhibit a low interpersonal distance and a corresponding loss of individual freedom of motion. Different simulating models are presented where concurrent groups of simulated agents interact in a modeled environment of the Al-Masjed Al-Nabawy with potential to enable direct acquisition of statistics and indications at levels of detail and accuracy. A series of simulation scenarios are carried out to provide an assessment of the effectiveness of existing systems

The paper is organized as follows. Section 2 discusses problem description and crowd risk analysis. Section 3 describes proposed modeling and simulation System. In Section 4, simulation results are presented. Finally, conclusions are drawn in Section 5.

## 2. Problem Description

To control entry to an area, some sort of barrier should be put around the site. The crowd needs to access an area and leave the masjid by another gate after the visit has finished. The entry and exit points will be of limited throughput, and they need to be of sufficient capacity to minimize the risk of crushing on entry or exit. These entry/exit points affect the rate of fill, and if the high-density areas fill too quickly the situation becomes in considerable risk.

## 2.1 Crowd Risk Analysis

There are several considerations for the crowd risk analysis: site capacity, movement pathways, entry and exit systems, and facilities management during normal and emergency situations.

*Site capacity:* is typically calculated based on the available area, the suitability of that area, and the rates of evacuation in an emergency. Site capacity also based on physical and safety considerations for a site.

*Movement pathways:* Arrangements that result in unbalanced use of entry or exit routes, dead ends, or similar confusing pathway choices, are not acceptable.

*Entry and exit points:* If the arrival flow rate exceeds the entry system capacity, then a queue will develop. This results in a gradual build-up of crowd density over time. As the crowd/queue size grows, the density at the front part of the queue will be compressed. This increases the crowd density. As crowd density increases to above six or seven people per square meter, the crowd reaches a point at which individuals experience physical contact and pressure.

## 2.2 Crowd Flow to Rawdah and Ziara Place

At peak times, regulating the access to Rawdah and Ziara place requires special attention. In order to control entry to this area, some sort of barrier is put around the site. The entry and exit points will be of limited throughput, and they need to be of sufficient capacity to minimize the risk of crushing on the entry point. The whole area Al-Masjed Al-Nabawy, including Rawdah and Ziara place (in the old masjed area) is shown in Fig. 1.

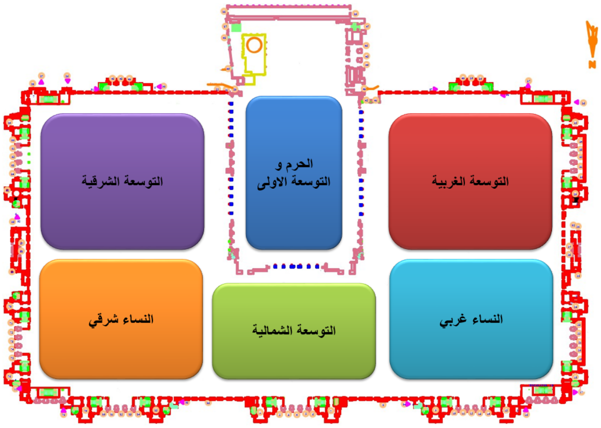


Fig. 1: The whole area Al-Masjed Al-Nabawy, including Rawdah and Ziara place.

## 3. Proposed Modeling and Simulation System

The problem of simulating the dynamics of large, dense crowds in Rawdah and Ziara Place is handled using the proposed modeling and simulation system of Al-Masjed Al-Nabawy, which focuses on Rawdah and Ziara place.

The processes structure of the model is shown in Fig. 2. In this modeled environment of the Al-Masjed Al-Nabawy, concurrent groups of simulated agents interact with potential to enable direct acquisition of statistics and indications. The main processes of the model include:

- Pedestrian Source: Generates pedestrians and is used as a starting point of the pedestrian flow. It allows defining group size, groups arrival rate, pedestrian interarrival delay, etc.
- Pedestrian Wait: Causes pedestrians to go to the specified location and wait there for a specified period of time.
- Pedestrian Go to: Causes pedestrians to go to the specified location, which can be de fined by a target line, area or a point with given coordinates.
- Pedestrian Sink: Disposes incoming pedestrians and is used as an end point of the pedestrian flow.


Fig. 2: The processes structure of the model: (a) in the men's area and, (b) in the women's area.

Fig. 3 shows the main screen of the proposed simulation system, which has slide-bar controls to allow controlling parameters of the systems. These parameters model include:

- Rawda Rate: controls the pedestrian rate for entering Rawdah (pedestrian/hour).
- Zeyara Rate: controls the pedestrian rate for Ziara place (pedestrian/hour).
- Women Rate: controls the pedestrian rate for women entering from eastern, western, northern east, and northern west gates (pedestrian/hour).

- Men_N_Rate: controls the pedestrian rate for men entering from northern gates (pedestrian/hour).
- Men_W_Rate: controls the pedestrian rate for men entering from western gates (pedestrian/hour).
- Men_E_Rate: controls the pedestrian rate for men entering from eastern gates (pedestrian/hour).

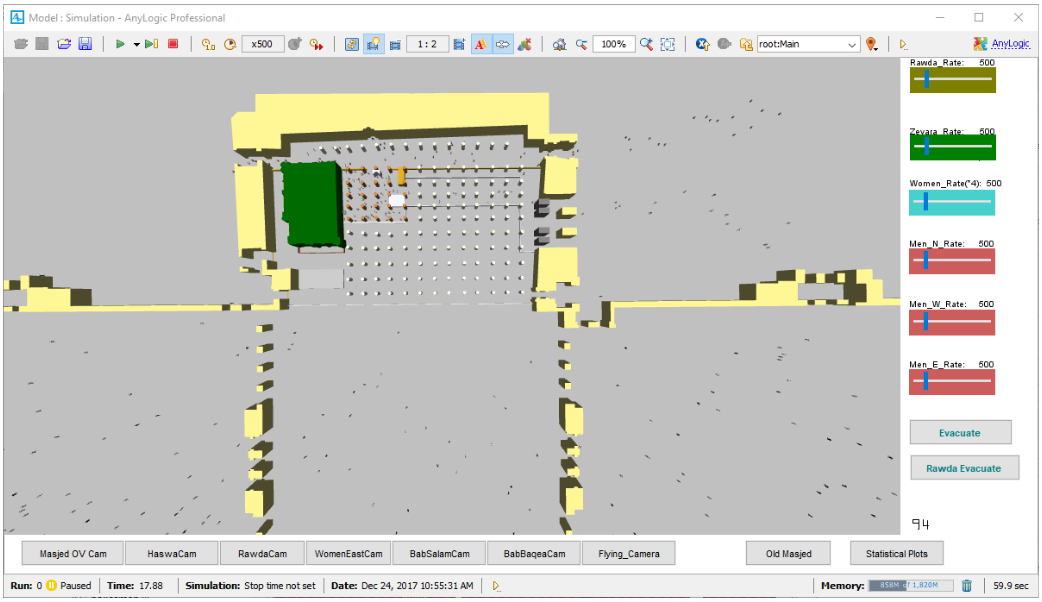


Fig. 3: The main screen of the proposed simulation system.

As shown in Fig. 3, the main screen has control buttons to allow controlling active camera viewport. The system has several cameras, which include:

- Masjed OV Cam: a camera that shows the whole area of the masjed.
- Hasswa Cam: a camera that shows the Haswa area.
- Rawda Cam: a camera that shows the Rawdah area.
- Women East Cam: a camera that shows the women's eastern area.
- Bab Salam Cam: a camera that shows Bab Al-Salam area.
- Bab Baqea Cam: a camera that shows Bab Al-Baqea area.

Examples of camera viewports of the system are shown in Fig. 4.

The main screen has, also, a control button (Statistical Plots) that shows some statistical graphs of the system.

## 4. Simulation Results

A series of simulations are carried out in order to test the behavior of the model. In this section an example of simulation scenario is presented. Experiment time, for this simulation is 120 min.

This experiment focuses on Rawdah and Ziara Place. The used pedestrian rate for entering Rawdah (Rawda Rate) is 1500 pedestrian/hour, while the used pedestrian rate for Ziara place (Zeyara Rate) is 1500 pedestrian/hour.

A screenshot of the system at time (120 min.) is shown in Fig. 5. A density map of Rawdah and Ziara Place area, after two hours running, is shown in Fig. 6.

The calculated statistics include the following:

- Bab Salam In: the number of pedestrian that have entered through Bab Al-Salam at a given time.
- Bab Baqea Out: the number of pedestrian that have exit through Bab Al-Baqea at a given time.
- Bab Salam_traffic: pedestrian rate that have entered through Bab Al-Salam (pedestrian/hour).
- Bab Baqea_traffic: pedestrian rate that have exit through Bab Al-Baqea (pedestrian/hour).
- Rawda In: the number of pedestrian that have entered Rawdah at a given time.
- Rawda Out1: the number of pedestrian that have exit through Rawdah Gate1 at a given time.
- Rawda Out2: the number of pedestrian that have exit through Rawdah Gate2 at a given time.
- Rawda In_traffic: pedestrian rate that have entered Rawdah (pedestrian/hour).
- Rawda Out1_traffic: pedestrian rate that have exit through Rawdah Gate1 (pedestrian/hour).
- Rawda Out2_traffic: pedestrian rate that have exit through Rawdah Gate2 (pedestrian/hour).

The calculated statistics, after running the simulation for two hours, are shown in Fig. 7.

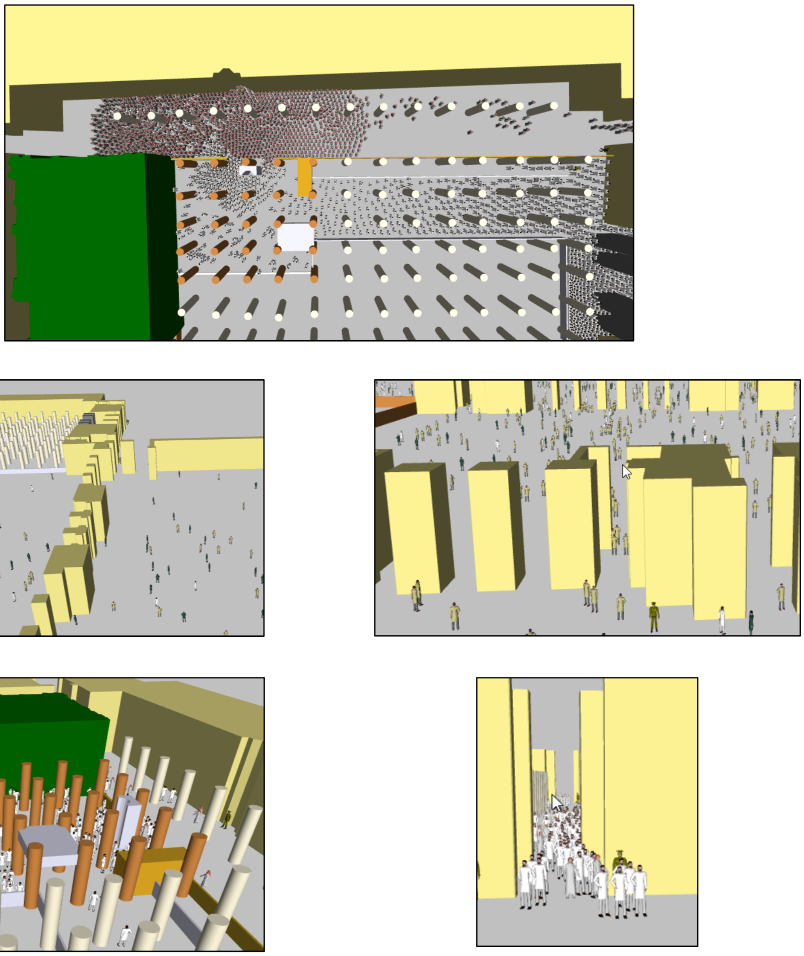

Fig. 4: Examples of camera viewports of the system.

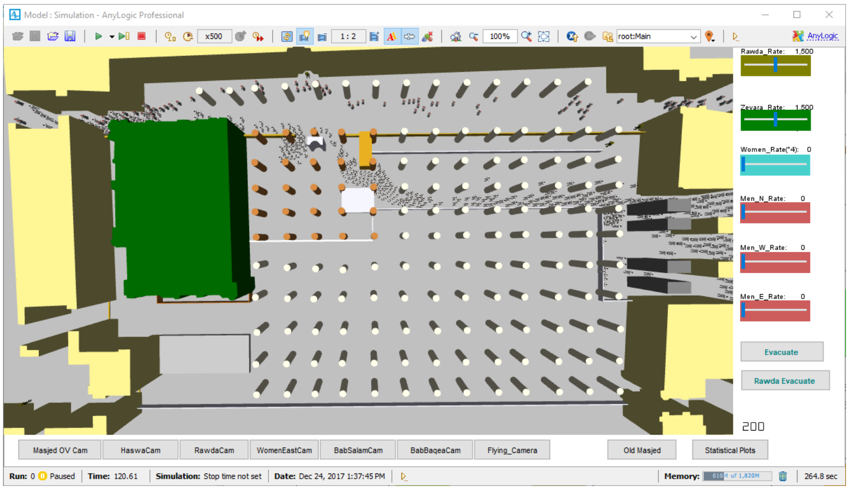


Fig. 5: A screenshot of the system at time (120 min.)

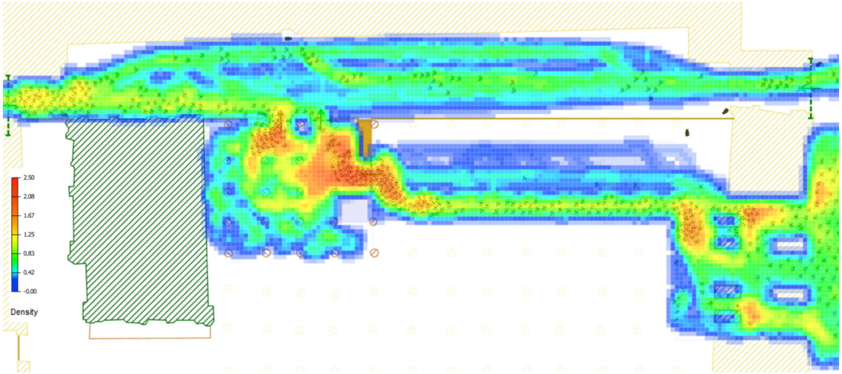


Fig. 6: Density map of Rawdah and Ziara Place area, after two hours running

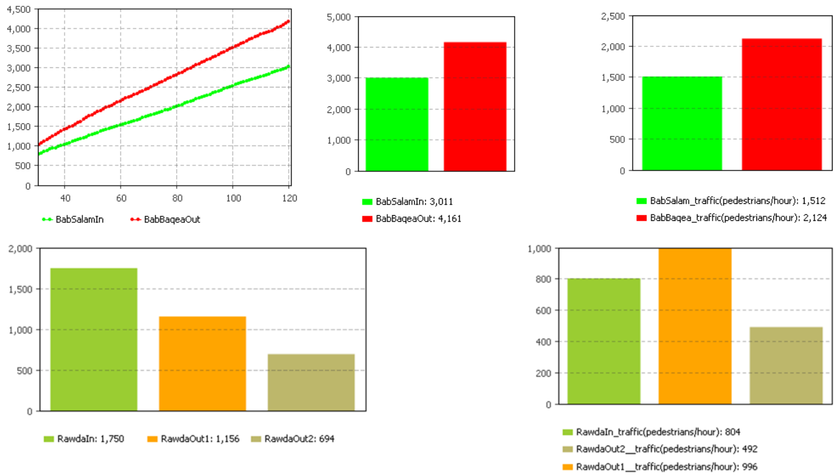


Fig. 7: Simulation results, after running the simulation for two hours.

## 5. Conclusions

In this paper, a modeling and simulation system of Al-Masjed Al-Nabawy, which focuses on Rawdah and Ziara place, has been presented. Concurrent groups of simulated agents interact in the modeled environment of the Al-Masjed Al-Nabawy with potential to enable direct acquisition of statistics and indications at levels of detail and accuracy. A series of simulation scenarios have been carried out to provide an assessment of the effectiveness of existing systems. The obtained results can also contribute in proposing alternatives systems, as well as, the possibility of developing indicators and readings to support decision makers.

## Recommendations:

It is necessary to apply studies that are based on modeling and simulation using computers to evaluate any proposals for the arrangements of entry, exit, or visit to the Prophet's Mosque (and the Holy Mosque), as modeling and simulation provide:

- indicators and readings that can evaluate the effectiveness of existing systems and identify their advantages and disadvantages.
- an initial view for decision makers that helps in evaluating the development plans to be implemented to overcome the high costs of real experimenting.
- The possibility of detecting obstacles or potential accidents that are not considered during the planning phase, and the possibility of providing solutions that reduce the effects of obstacles, which can be avoided if foreseen using modeling and simulation.

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