Proceedings of the 2013 Winter Simulation Conference
R. Pasupathy, S.-H. Kim, A. Tolk, R. Hill, and M. E. Kuhl, eds

ANALYTICS DRIVEN MASTER PLANNING FOR MECCA: INCREASING THE CAPACITY WHILE MAINTAINING THE SPIRITUAL CONTEXT OF HAJJ PILGRIMAGE

Cenk Tunasar

Booz Allen Hamilton
8283 Greensboro Drive,
McLean, VA 22102, U.S.A.

ABSTRACT

Approximately 3 million pilgrims visit Mecca in Kingdom of Saudi Arabia each year to fulfill a religious obligation and perform rituals concentrated around few iconic Muslim landmarks, including Kaaba. Mecca is unarguably the most congested public space in the world with densities often exceeding 6 people per square meter causing comfort, safety and security issues. This dense concentration of people in a short time period calls for careful design and operational planning to ensure safe, secure and efficient pilgrim movements. We used queuing theory to determine the feasibility of options, discrete-event simulation to mimic the pilgrim movements, traffic flow theory to understand macro movements across town, and vehicular simulation models to test the concepts for mechanized movement solutions for elderly and handicapped. The master plan analytics formed the basis for architectural design and alterations. The overall design is able to provide a safer and more efficient journey for pilgrims.

1 INTRODUCTION

We describe an analytics driven master planning effort to improve crowd movements in the holly city of Mecca in Kingdom of Saudi Arabia. We will explain the work context, articulate the purpose of the project, describe our methodology, demonstrate our results and highlight the impacts of this analytics driven master planning process in the successful design for expansion.

The project was initiated as a design competition among multiple international firms in September 2010. An advisory and judging panel was formed comprised of technical experts in crowd control, local Saudi Mosque operational staff, Saudi Ministry of Higher Education, and other experts and project stakeholders to ensure a balanced design with respect to mobility, safety, comfort and security. This advisory board evaluated and down-selected multiple design-teams, and finally choose two design teams to move forward with the facility design and planning project. The work presented in this paper describes the analytics component of the team's master planning framework.

1.1 Background on Hajj

This section provides a background on Hajj, one of the five pillars of Islam (Ministry of Haj 2013). The history of Hajj dates back many centuries before the message of Prophet Muhammad, when Prophet Ibrahim (Abraham) and his son Ismail (Ishmael) built the Kaaba, "the House of God" and called people to a pilgrimage to it. Until today, the pilgrimage is a result of peoples' response to that call and 'the House' became the Qibla, the direction of worshipers' daily prayers. The pilgrimage (Hajj) to Mecca (Kingdom of Saudi Arabia) is a once in a lifetime obligation for Muslim worshipers who are physically and financially able to perform it. Hajj, one of Islam's five pillars, induces the gathering millions of worshipers at the same time in the Holy Mosque in Mecca. Mecca is located 70 km inland from Jeddah in a narrow valley at a height of 277 m above sea level. Its resident population in 2012 was 2 million, although visitors more than triple this number every year during Hajj period held in the twelfth Muslim lunar month of

Dhu al-Hijjah. As the birthplace of pilgrim Muhammad and a site of the composition of the Quran, Mecca is regarded as the holiest city in the religion of Islam.

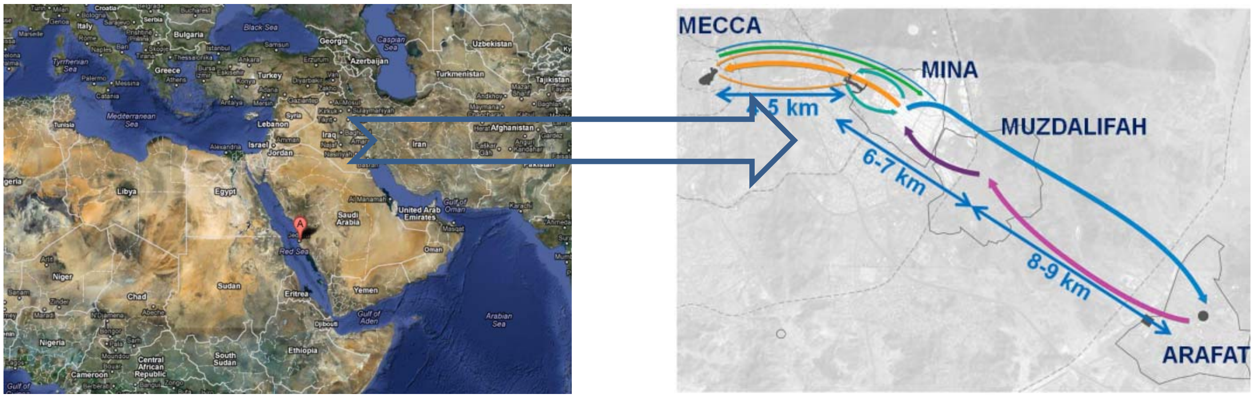

Figure 1: Holly sites in Mecca**.** Mecca is located in Saudi Arabia (top), and the pilgrimage sites cover the corridor between Mecca and Arafat. The central point of Hajj is the Kaaba where crowds merge to perform rotation around the iconic structure.

More than three million worshipers from around the globe go to Mecca each year to perform Hajj. Tawaf, or circumambulation of the Kaaba, the focal point of the Holy Mosque, is the cornerstone of Hajj rituals. Performing Tawaf requires circulating Kaaba 7 times in counter clockwise direction mainly in a space around Kaaba called Mataf. The number of worshipers has reached figures which raised concerns related to the ability of the available spaces to safely accommodate the rituals of Hajj and Umrah namely Tawaf. Significant difference in terms of capacity is documented between the Mataf and rest of the spaces within which other rituals are performed. The Mataf is mapped as the bottleneck amidst the different liturgical areas given not only its limited area but also its significance as the main ritual to be performed during Hajj and Umrah. According to statistics issued by the Custodian of the Two Holy Mosques Institute of Hajj Research, there are about 40,000 people per hour during peak periods at the rate of six people per square meter performing the Tawaf (circumambulation around the Holy Kaaba) in the Grand Mosque in Makkah Al Muqarramah.

The pilgrimage to Mecca attracts millions of Muslims from all over the world. There are two pilgrimages: the Hajj, and the Umrah. The Hajj, the 'greater' pilgrimage is performed annually. Once a year, the Hajj, the greater pilgrimage, takes place in Mecca and nearby sites. Every adult, healthy, sane Muslim who has the financial and physical capacity to travel to Mecca and can make arrangements for the care of his/her dependents must perform the Hajj once in a lifetime. Umrah, the lesser pilgrimage, is not obligatory, but is recommended in the Qur'an. Often, they perform the Umrah, the lesser pilgrimage, while visiting the Masjid al-Haram.

The Grand Mosque has undergone several expansions throughout the history of its development. These expansions were a response to the spatial needs the increasing numbers of worshipers are inducing. However, the Mataf (central point of the Mosque) remained the most challenging space to expand due to many parameters: spatial, architectural, structural, historical, managerial, etc. In order to develop a solution for increasing the capacity of the Mataf, this document starts by mapping Islamic rituals in and around Makkah Al Muqarramah and the related statistics. The characteristics of Makkah, the Grand Mosque and the Mataf will introduce the need for such studies for expanding the capacity of the Mataf.

1.2 Current issues, needs and the purpose of the project

There are currently over 3 million pilgrims visiting Mecca to perform Hajj and Umrah and transit through a 20-mile stretch of land mostly on foot, and concentrate around few iconic structures, especially the Kaaba where pilgrims walk around this structure 7 times. The existing throughput rate is ~40,000 pilgrims per hour within the Mosque with extremely dense crowds in excess of 6 people per square meter. Such densities are never heard of at other planned crowd activities (Fruin 1987; Hall and Hall 1995). This brings the challenge of safety, security and comfort. Figure 2 shows a typical day in Hajj.

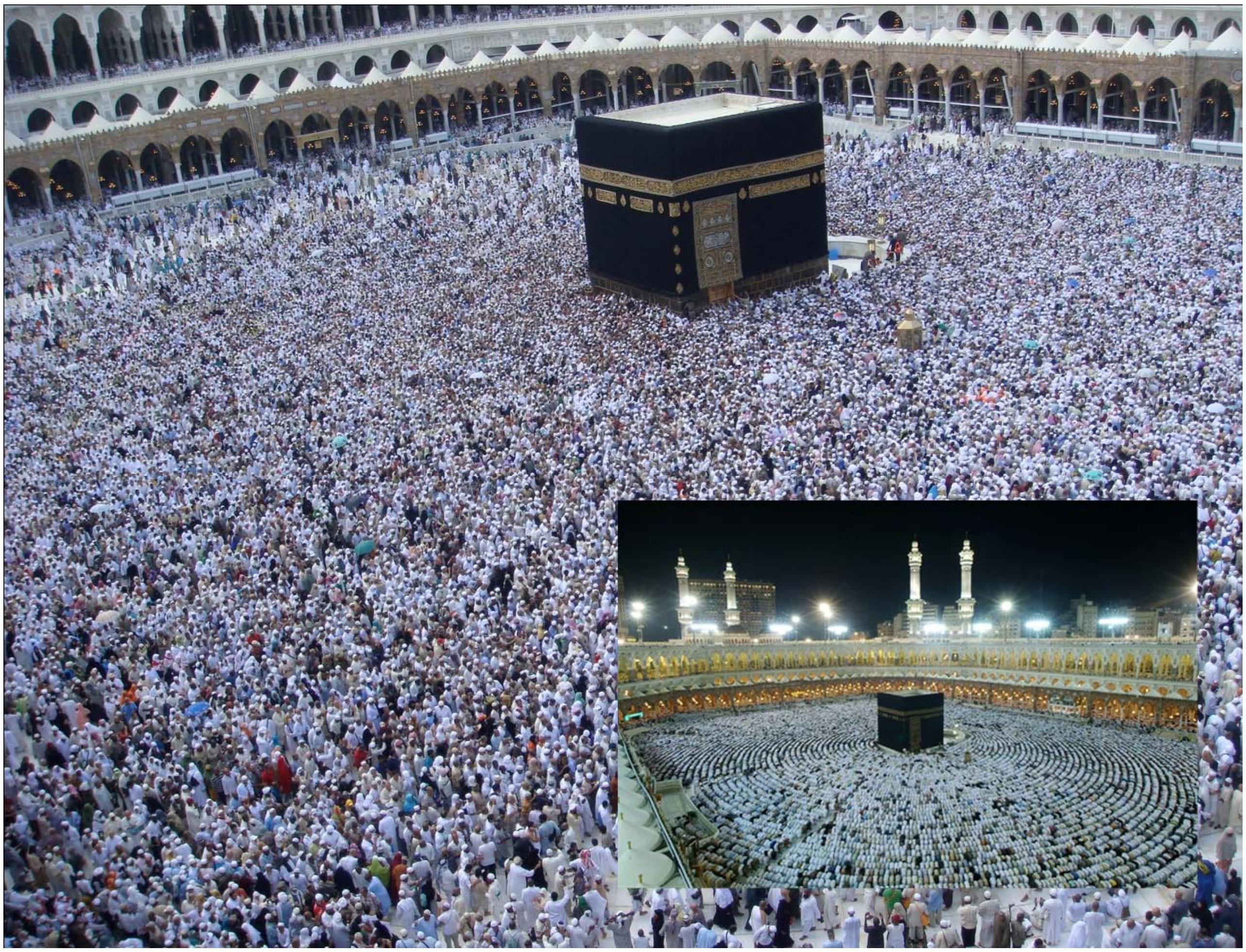

Figure 2: Congestion around Kaa'ba. Extreme crowding around Kaaba, densities are observed to exceed 6 people per square meter, there is a counter-clockwise rotation around the structure and constant inflow and outflow creating merge challenges. Five times a day, crowds get in praying formation as shown on the lower right.

What makes the situation even more complex is that the demographics of the pilgrim population are varied across nations with different culture and languages, different age groups especially many elderly and disabled visitors. While the crowds in general move homogeneously around Kaaba, they stop the circular motion 5 times a day and pray at specified time intervals that necessitate the crowds to expand from their dense movement formation towards a less dense praying configuration. In a sense, the crowd contracts and expands, and the design and operational rules should be able to allow for such diverse use of the available space.

The study was commissioned in phases with the overall goal of expanding the capacity of this holly infrastructure while maintaining safe, secure and comfortable transit and experience. There were two distinct phases of the study each with similar but slightly different objectives:

1. Holly Mosque capacity increase: Double the capacity of the existing mosque while maintaining spiritual, safety, security and mobility standards.
2. Provide separate visitation system for people with special needs: Develop an automated people movement system to be able to provide equal access to all pilgrims.

All phases of the project support a unified goal of approximately doubling the capacity of this religious site while improving existing conditions with respect to mobility, safety, security, comfort and spiritual context. This is in essence a multi objective optimization problem with conflicting decision variables. For example, if one is concerned with safety, it is best to design the space with at least 1 square meter per pilgrim personal space, but that would mean a 6 fold decrease from today's throughput with 6 people per square meter. There are also comfort issues due to environmental condition, the air temperature reaches 120 F during summer months.

The role of analytics and modeling in this project was to objectively assess alternatives and guide the master planning of the site to achieve a capacity of over 100,000 pilgrims per hour at the mosque and achieve an increase from 3 to 5 million annual pilgrim visitations for Hajj. Rest of the paper describes the analytics framework used in achieving the project objectives.

2 METHODOLOGY

While traditional building design or city planning requires analyses of needs, the use of advanced analytics techniques including queuing models or simulation is not common. Facilities are often designed by architects and engineers through well-established standards such as required number of doors for a building of a given size. While this approach may be applicable to most cases, there are situations where the facility requirements are unique, such as the case for Mecca, that necessitate a more integrated modeling approach. The use of flow theory and detailed simulations is not new, it has been successfully applied to facility planning as exemplified by the use of discrete event simulation modeling for airports, train stations, sport arenas. There is specialized simulation software available to use in such settings. However, none of the existing tools or methodologies supported a direct application for the crowd densities that are considered for Mecca, it required a specialized modeling framework to not only test the design, but to drive the design process through rapid scenario analysis. There are limited modeling and simulation work performed at Mecca in this context, including work describing the relationships of crown behavior and movement (AlGahdi and Mahmassani 1991).

Initially, we used a multi-resolution analytics and modeling framework shown in Figure 3. What is noteworthy to mention is that the analytics framework supported the design from idea inception through detailed design. The proposed four levels of modeling demonstrated that modeling is not reserved for one particular stage of master planning process; rather it was an instrument to guide the overall design. For example, at the early stages of the design, we developed and used a queuing theory based crowd modeling approach to eliminate infeasible designs early on. Analytics improves design by defining observed movements, simulating movements in proposed spaces, examining simulated outputs, and interpreting findings in order to inform design decisions. Crowd simulations include four distinct modeling techniques for design validation purposes: constraint satisfaction, queuing models, agent based models, and micro-simulation with animation. Figure 3 shows the different levels of analytics and modeling used throughout the master planning process.

Analytics improves facility design by defining observed movements and associated variables, studying movements in proposed spaces, examining results under operational changes, and interpreting findings in order to inform design decisions. An essential component of the facility design is the assessment of the proposed design alternatives with respect to occupancy, level of service and throughput. We developed and employed a wide set of analytics to ensure that the proposed design meets and exceeds the design guidelines and that the pilgrims will have safe and comfortable experience within the Mosque. Throughout the study, Analytics informed the design process by quantifying the level of service with respect to the following parameters:

	Level 1 (Flow Algebra, Constraint Identification)	Level 2 Queuing Theory, Spreadsheet Model	Level 3 Detailed Simulations, Agent Based Modeling	Level 4 Animations
Goal	▸ Quickly eliminate infeasible options ▸ Help the design team focus on feasible options and advance designs	▸ Use analytics and modeling as a back bone of the design process ▸ Quantify the level of service for a dozen options	▸ Assessment of the selected design ▸ Identify choke points, develop remediation options	▸ Provide a visual for problem areas ▸ Demonstrate how the proposed design fulfills objectives
... the following modeling techniques are used	▸ Inventory all existing modeling and analytics work ▸ Basic algebra on Tawaf capacity, impact of 4 vs. 7 people per square meter	▸ Queuing theory, Little's rule ▸ Develop a spread sheet model ▸ Rapid testing of options	▸ Use VISSIM Pedestrian for select areas (ground floor) ▸ Social force model ▸ Compare results with flow model	▸ VISSIM detailed crowd modeling ▸ ARENA discrete event modeling, mimicking meso-micro scale modeling
... with outcomes such as...	▸ Effectively eliminating multiple design options ▸ Helped the design team focus on feasible options and advance designs	▸ Spread sheet model ▸ Occupancy ▸ Tawaf times ▸ Throughput	▸ More realistic Tawaf times ▸ Crowd dynamics and choke points ▸ Level of service measures for areas	

Figure 3: Analytics Framework for Master Planning

- Available space per pilgrim, crowd density
- Walking speeds, Tawaf Time (circling around Kaaba)
- Ease of access and egress from levels, vertical circulation

Our approach to capacity extension was staged through a conservative addition as shown in Figure 4.

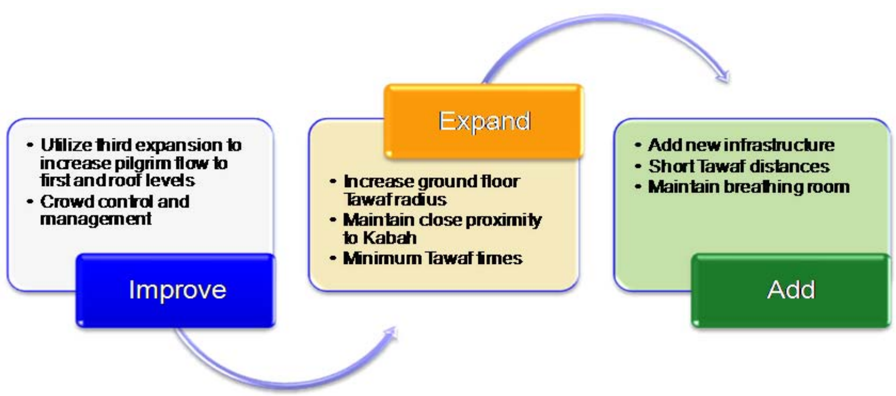

Figure 4: Capacity Expansion Stages

First we looked at options to improve the existing capacity through operational changes and re-directed flows to different levels and tested the utility of this through micro-simulations. Next we considered expanding capacity by adding more ground floor area near Kaaba that maximizes throughput due to the close proximity. In order to achieve the desired capacity goal, we also added a new level to the mosque.

There are a variety of detailed simulations that may be used in a study like this, and most available models in the literature are not readily applicable (Al Tassan and Al Saudi 2008). Our team did not want to rely on one simulation model and developed this multi-phased approach. The cornerstone of our approach is the robust queuing theory model that is validated through detailed simulations (VISSIM, ARENA and AnyLogic). While detailed simulations are very valuable to uncover spot problems, they have a tendency to over or under-expose the problem, hence a more robust and steady approach of queuing theory validations was necessary.

There were many challenges in using traditional discrete-event simulations. The problem space is extremely large, over 100,000 active entities is very difficult to model and run. We coded the people movements in multiple simulation languages as none of the COTS (Commercial off the Shelf) tools were easy to apply as none were designed to deal with crowd densities that we modeled, in excess of 4 people per square meter. A significant challenge is to code the entity (pilgrim) collision avoidance. We initially ignored collision avoidance and develop rapid executing simulation models only to realize that the results were significantly incorrect when compared to on-site GIS based data collection (Koshak and Fouda 2008). Collision avoidance was critical in expressing the weaving of pilgrims within the crowd. With collision avoidance modeled (by tools VISSIM and AnyLogic), the modes produced valid results but extremely slow, rendering their utility for multiple sensitivity runs. On an Intel 16 Core server with 64GB main memory (typical current high speed server in 2011), run times were 10-20 times slower than real time. One day of replication took over 2 weeks to run, clearly an unacceptable situation. We designed the simulation models as continuous simulations with 4 hour transient time and utilized batch means method during the steady state for confidence intervals. Figure 5 depicts the simulation model animation screen capture.

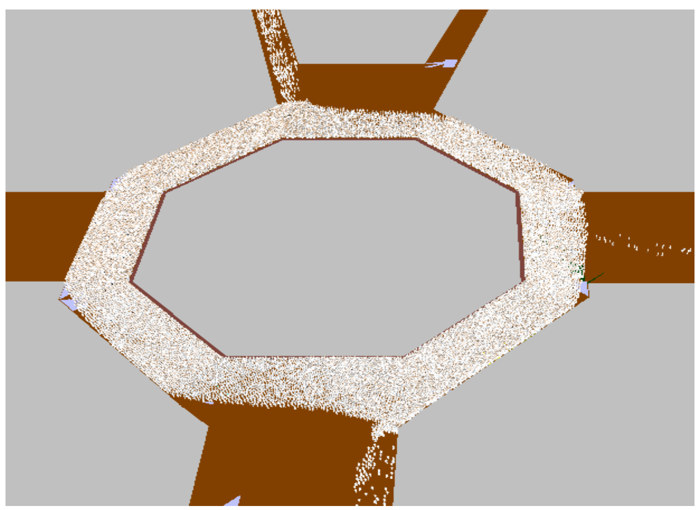

Figure 5: Simulation Model Animation. The screen shot from animation shows the crowding on the new proposed octagon shaped floor designed on top of the existing Mosque. Pilgrims enter the circulation from top and bottom and after 7 rotations, exit from right as seen in the figure. Each white dot is a 3D rendering of pilgrims and there are approximately 20,000 pilgrims present in this screen capture. The animation is recorded in the simulation speed which is 10x slower than real time but sped up through video editing software.

While the simulation was very helpful in identifying choke points and quantifying issues, it was not robust and flexible to assist rapid evaluation of ideas. A very simple but effective queuing rule known as Little's Rule formed the basis of early evaluations. Simply put, the rate of arrival to system multiplied by the time spent in it equals the number of pilgrims present. This provides a great way to test multiple alternatives (over 20) rapidly. The density of 4 people per square meter is a design goal and with the proposed architecture, we are able to calculate the number of people that can fit to a given area. The crowd densities determine the walking speed which in turn determines the amount of time spent in the facility. Knowing occupancy and time spent makes it trivial to compute the arrival (or departure) rate from the system.

3 RESULTS

We achieved the design target of doubling the capacity of Hajj at the Mosque through operational changes and capacity additions and exceeded the goal of 100,000 pilgrims per hour while maintaining the design standards.

Proposed Mataf design with added levels to Mosque doubles throughput capacity to 102,000 persons per hour. This capacity is achieved with the target design density of 4 people per square-foot. The capacity is distributed across multiple floors although majority of Tawaf capacity is provided at ground, 1st and roof floors. A unique feature of the proposed capacity is that different levels have varying access/ egress characteristics enabling better capacity management and segmentation of crowds. Each floor can be closed-off to pilgrims for maintenance activities while still providing a flexible Tawaf area. Another key point to note is that the provided 102,000 pilgrims per hour Tawaf capacity if still closely centered around Kaaba, offering reasonably short Tawaf durations.

Capacity growth of the Mataf through combinations of improvement, expansion, and addition of space is balanced with other design priorities, including preservation of atmosphere and coordination with previous and planned structural expansions. Delivered capacity reduces average density of Tawaf areas to four pilgrims per square meter (from 7 people per square meter) hence improving safety and Tawaf experience. 14% of capacity increase is obtained through improvements to existing structure and enhanced access and egress, 18% through expansion of existing Tawaf area, 50% through capacity additions, and 21% through operational control of worshiper flow. The distribution of the achieved capacity among different sections of the Mosque is shown in Figure 6.

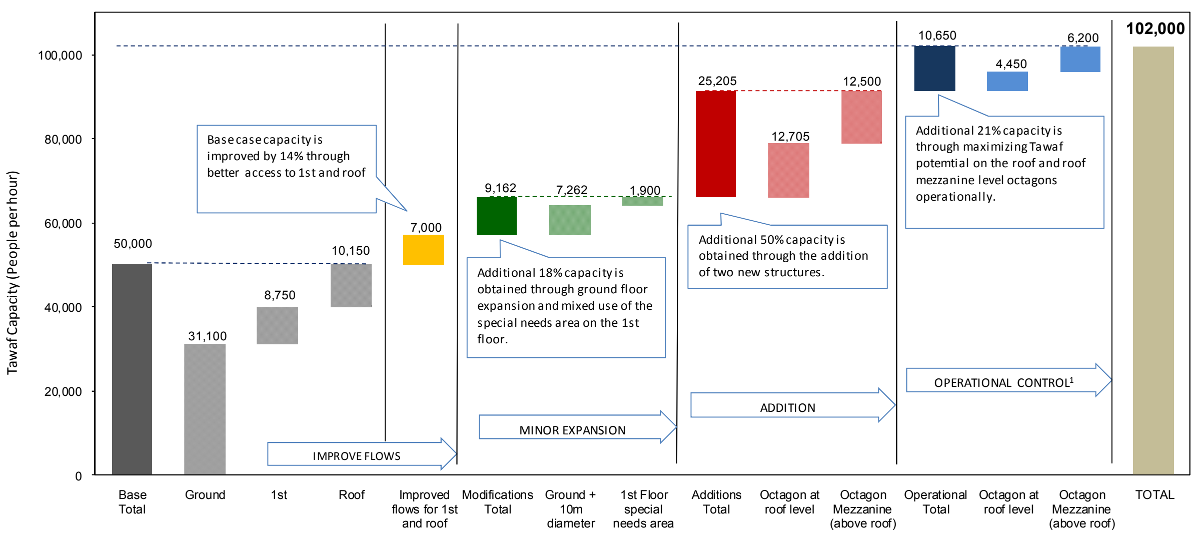

Figure 6: Throughput Increase by Sections of Infrastructure

While the capacity is doubled, the TAWAF times are only increased slightly by 10%, a significant achievement accomplished by adding capacity close to the center location. The additional Octagon structures designed around Kaaba have shorter Tawaf times than 1st and roof floors, providing a better level of service. Figure **7** shows the minor increase in experience times while the capacity was doubled.

Besides enabling the design team to determine the required size and location of expansion, another important aspect of the modeling is to identify potential bottlenecks when the architecture team produces the facility drawings. For example, an addition of a structure above roof to accommodate more pilgrims was decided based on the modeling results, however, the actual shape of the space is very important in its ability to support the throughput rates planned. Using queuing theory, we identified the need for an additional 20,000 square meter flow space and the design team was able to achieve that through two concentric circles.

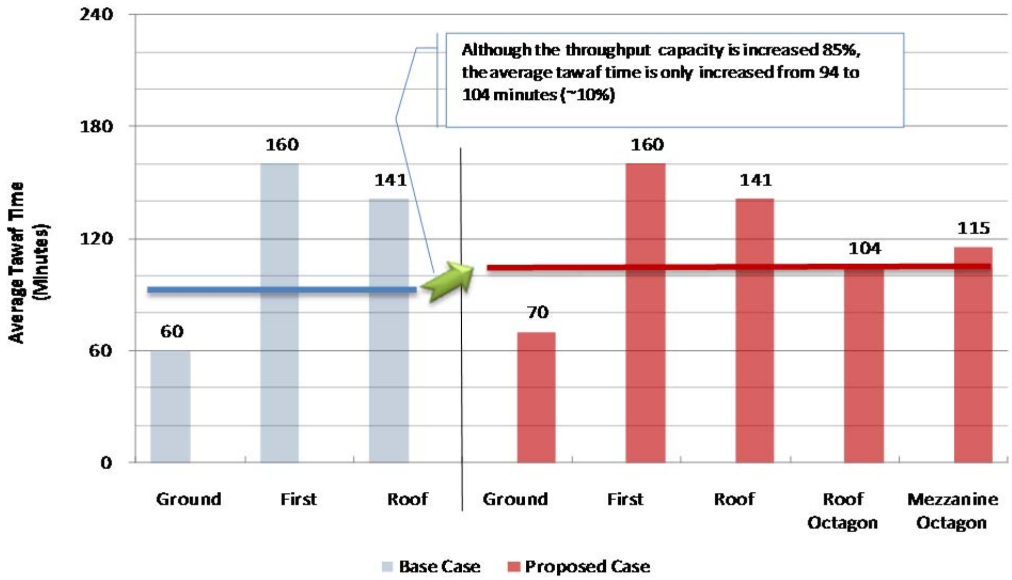

Figure 7: Pilgrim Experience Duration

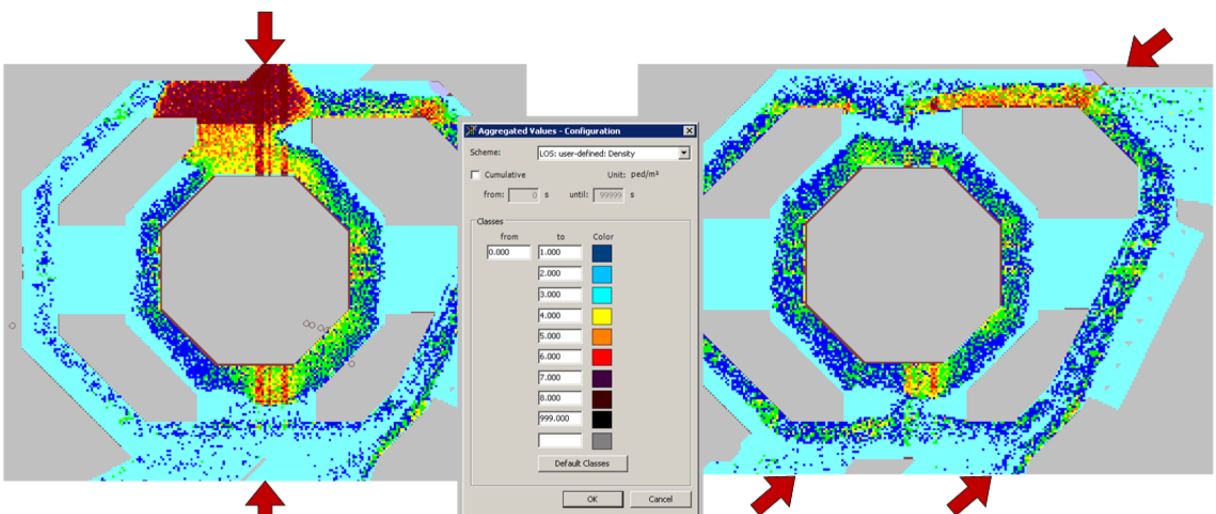

Figure 8: Bottlenecks in Flow through Heat Maps from Simulation

Figure 8 demonstrates the congestion points at the entrances to the circular rotation points, especially on the top side. Red notation in the figure (left side) denotes poor level of service with people densities reaching 8 people per square meter. Through several "what-if" analyses using the discrete-event simulation model, we were able to alleviate this situation and improve level of service by shifting the entry points of the crowds (right side of Figure 8).

We also used the flow models to develop emergency evacuation planning, adhering to evacuation standards (AlGahdi and Mahmassani 1991; Still 2000). The simulation models provided the time it takes to evacuate all floors of the Mosque with associated animations.

In order to improve overall throughput and provide acceptable service to elderly and special needs population, we proposed to segregate the special needs group and designed a special floor and a people mover system. The goal was to design an automated system that can transit elderly and special needs pilgrims throughout the facility. While there are many examples of automated movement systems, especially for amusement parks, the situation here was quite different. Most pilgrims go to Hajj perhaps once in their lifetime, and over 90% or population were first time visitors, hence the usability of the automated people mover system is critical. Additionally, pilgrims are there to for a spiritual experience, and do not want to feel rushed. We developed flow models to evaluate a large number of possible speed-density combinations for the proposed automated system, and offered the stakeholder look-up tables to understand the range of possible technology that can achieve the desired movements. Figure 9 demonstrates the use of these speed-density curves and respective achievable throughput. A simple queuing model is used to rapidly generate these charts since simulation was once again too much time consuming. Following the convergence to a system with a conveyance speed of 10 km/h and a vehicle size of 2-4 people per vehicle; we investigated the possibility of autonomous driverless vehicles that are able carry occupants.

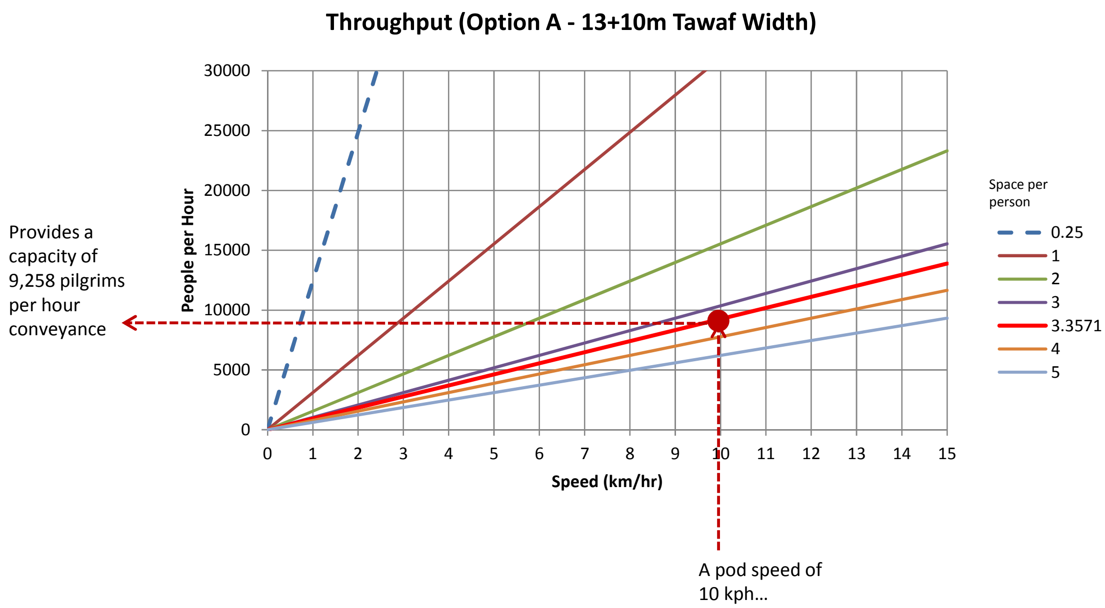

Figure 9: Speed-Density Look-up Tables for the Automated People Mover System

Due to safety and security considerations, the proposed automated movement system should be autonomous, can move without driver interaction, able to accelerate, stop, and turn without driver input. There are multiple emerging technologies that can offer that, with one example from General Motors Electric Networked Vehicle (EN-V). Once the basic speed-density requirements are determined, the throughput of this proposed automated system is tested through micro-simulations and supported 15,000 special needs pilgrims per hour throughput. Available vehicle traffic simulation tools such as VISSIM, TRANSIMS are validated traditional highway type vehicles and did not provide acceptable results under this custom vehicle scenario. We then used AnyLogic COTS tool and tested the impact of vehicle weaving on throughput. While we were able to prove the general concept of operation for the automated vehicle system, more work needs to be performed on vehicle interactions through detailed simulations.

All proposed changes in this study are tested for implementation feasibility including the examination of structural requirements (load bearing walls and structures) as well as environmental, safety and security impacts. Structural feasibility was especially important as the added capacity was on a new level that is free standing and supported by new columns. Also, the proposed people mover solution required careful examination of structural and safety considerations. Validity of the proposed changes are established both internally through the use of subject matter experts in safety, security, environmental and structural, but also with external project stakeholders.

4 IMPACT AND CONCLUSIONS

We were tasked to double the capacity of Hajj at the Grand Mosque, and provide good level of service for all pilgrims, especially special needs. We achieved this, doubled the capacity to over 100,000 pilgrims per hour, and improved the comfort by providing more space per pilgrim in their journey that enabled them to experience improved spiritual context. The impact of Analytics in this project including queuing theory models, discrete-event simulations and vehicle flow modeling is multiple-fold. First, analytics and modeling was used as a center piece and integrated with the architectural design process, an improvement over the traditional way where modeling is only used to test operations post design. Second, it allowed an unbiased assessment of the proposed designs, allowed us to clearly rank options. Finally, the modeling and related visualizations and animations created a highly collaborative design environment where the client and design team stayed engaged all throughout the project.

There were challenges, especially in the use of detailed simulations. While discrete-event simulations are widely used, their utility in extremely customized situations such as the people flows in Mecca, are limited. Even with today's high performance computing power and algorithms, detailed simulations can be extremely complex and time consuming. When a simulation model's time steps are 20 fold slower than real time, the need for it diminishes. Additionally, simulating people movements are more difficult than manufacturing or other industry modeling due to complex people behavior.

ACKNOWLEDGMENTS

The overall project success depended on multiple key individuals. We thank the architectural firm Gensler in their vision and delivery, especially Bill Hooper, Don Ghent, Riko Arsiananta and Kian Shamloo. Our client including Ministry of Higher Education and SETS deserve appreciation in their vision and assistance throughout the project. Special appreciation goes to Dr. Hani Mahmassani for diligently reviewing the analytics content and providing input, to Abdulrahem H. Al-Zahrani and Dr. Isam Kaysi for their constructive comments and direction.

REFERENCES

Al Tassan, A., and I. Al Saudi. 2008. "Report on Means of Evacuating the Occupants of Holy Mosque," in *Makkah During Panic or Hazardous Events,* Prepared by the Architectural and Safety Committee For The Ministry of High Education, Kingdom of Saudi Arabia.

AlGahdi, S. A. H., and H. Mahmassani. 1991. *Simulation of Crowd Behavior and Movement: Fundamental Relations and Application.* Transportation Research Record.

Fruin, J. 1987. *Pedestrian: planning and design*, revised edition, Elevator world inc., Mobile, Alabama.

Hall, M. R., and E. T. Hall. 1995. *The Fourth Dimension in Architecture: The Impact of Building on Behavior.* Santa Fe: Sunstone Press.

Koshak, N. A. and A. Fouda. 2008. "Analyzing Pedestrian Movement in Mataf Using GPS and GIS to Support Space Redesign," *Proceedings of the Ninth International Conference on Design and Decision Support Systems (DDSS) in Architecture and Urban Planning*, The Netherlands.

Ministry of Haj. 2013. Information Website. Kingdom of Saudi Arabia. Accessed 29 June 2013; http://www.hajinformation.com/main/m.htm.

Still, G. K. 2000. *Crowd Dynamic.* Ph.D. thesis, University of Warwick, Department of Mathematics.

AUTHOR BIOGRAPHY

CENK TUNASAR is a Senior Associate in Booz Allen Hamilton's Strategic Innovation Group leading a team of analytics professionals developing and delivering advanced modeling and simulation solutions. He has a domain experience in Infrastructure Planning and a functional expertise in Modeling, Simulation and Optimization. Dr. Tunasar has assisted numerous airport, airlines, transit clients, state and local governments with highly visible process modeling and optimization projects. He has over 10 years of experience on pedestrian simulation and level of service analyses, and regularly publishes and presents at conferences. He holds a Ph.D in Industrial Engineering/Operations Research from the University of Pittsburgh and an MS and BS in Industrial Engineering from the Middle East Technical University. His email is tunasar_cenk@bah.com.