Proceedings of the International Conference on Industrial Engineering and Operations Management

Publisher: IEOM Society International, USA DOI: 10.46254/GC03.20260354
Published: February 2, 2026

Crowd Management in Religious Gathering-Systems Design Approach

Shamsuddin Ahmed
Faculty of Engineering, Department of Industrial Engineering
Islamic University of Madinah, 42351, Kingdom of Saudi Arabia
Dr_Shamsuddin_Ahmed@Yahoo.Com

Abstract

This case study aims to enhance the visitor experience at Al-Rawdah Al-Shareefa, a religious site in Madinah, KSA, by identifying and addressing bottlenecks in the current visitor flow. We analyze current visitor flow and propose data-driven solutions to enhance the overall visitor experience. A mixed-methods approach was employed, including process flow analysis (Ahmed, 2021), Quality Function Deployment (QFD), surveys, and on-site observations. A comprehensive case study approach was utilized, involving process flow analysis. The study identified significant bottlenecks at security checkpoints and entry points, resulting in prolonged wait times and disruptions to the overall visitor flow. Additionally, visitor surveys revealed a strong desire for safety, security, organization, cleanliness, and a peaceful atmosphere. Bottlenecks and wait times in the visitor process flow revealed potential bottlenecks at security checkpoints and entry points, resulting in variable wait times (10-50 minutes and 5-30 minutes, respectively). The variability disrupts the overall flow and can significantly exceed the desired throughput time, potentially exceeding 100 minutes. The average wait time reported by pilgrims was 61 minutes, substantially higher than the ideal of 30 minutes.This research contributes to crowd management and religious tourism by applying practical and data-driven techniques to a specific religious site. The outcomes and approvals may be implemented on other analogous platforms to enhance visitor satisfaction and optimize resource allocation. In addition, the case study offers a unique perspective on event and crowd management for mega-events and is anticipated to lead to significant advancements in the design of comprehensive systems that prioritize safety and security in crowd control.

Keywords
Systems Design, QFD, Crowd Management, Waiting Time Reduction, Capacity Plan

1. Introduction:
Al-Rawdah Al-Sharifah holds immense religious significance for Muslims worldwide. This significant influx of pilgrims necessitates efficient crowd management to ensure safety, security, and a positive visitor experience. However, current visitor flow processes face challenges, including long waiting times and overcrowding (Ahmed and Memish, 2019; Almutairi et al, 2022). This study aims to analyze the existing system and propose data-driven improvements to streamline the pilgrim experience.

The strategic direction of Saudi Arabia, from the foundational period under King Abdulaziz bin Abdulrahman to the present day, with the Guardian of the two landmark Mosques, King Salman bin Abdulaziz, including the Crown Prince, has consistently focused on serving the guests of the Most Merciful by refining the quality of services provided to them. The two holy sanctuaries exemplify a unique model of the Kingdom's care for pilgrims, ensuring comprehensive attention to their needs. These efforts include the enormous projects to expand the two holy sanctuaries and enhance their services, in line with Vision 2030. The construction and expansion of the Sacred Mosque and the Prophet's Mosque were driven by the goal of enabling as many Muslims as possible to visit and perform their rituals fully.

Through thorough planning and engineering expertise, the Kingdom has undertaken numerous expansions to the two sacred sanctuaries, aiming to provide the highest level of service to visitors year-round.

The imperative to accommodate increasing visitor numbers requires robust crowd management strategies within the Prophet's Mosque. Saudi Arabia's Vision 2030 aims to raise the number of Umrah performers significantly to 30 million. This necessitates implementing effective crowd management practices to ensure the safety and well-being of visitors (Haghani et al., 2023). Crowd management is a multifaceted discipline that encompasses the planning, coordination, and control of large groups of people in public spaces (Alamri, 2018). Its application extends across diverse settings, including religious gatherings, concerts, protests, and political rallies. Effective crowd management is paramount for public safety and security (Haghani et al., 2023).

Research on crowd management draws on disciplines such as psychology, sociology, engineering, and computer science (Haghani et al., 2023). The researchers aim to optimize crowd management practices. This optimization leads to increased efficiency, reduced risk of accidents and emergencies, and an enhanced overall experience for participants in large-scale events. As the number of visitors continues to rise, effective crowd management within the Prophet's Mosque becomes increasingly critical, highlighting the need for ongoing research and development in this vital field.

Within the Prophet's Mosque, Al-Rawdah Al-Sharifah is a designated area experiencing exceptionally high concentrations of worshippers throughout the day. This heightened activity is attributed to two primary factors. Firstly, Al-Rawdah Al-Sharifah is believed to hold immense spiritual significance. According to a hadith of the Prophet, the space "between my house and the pulpit of Rawdah is from the gardens of Paradise" (Sahih al-Bukhari," Book 60, Hadith 430). Secondly, the limited area of Al-Rawdah Al-Sharifah, defined by the Prophet himself, contributes to its crowded nature. Historical accounts suggest the eastern boundary is demarcated by the house of Aisha, the western boundary by the Prophet's pulpit, the southern boundary by the qiblah wall, and the northern boundary by a line parallel to the end of Aisha's house (Sahih al-Bukhari," Book 60, Hadith 430). Al-Rawdah Al-Sharifah's compact size, estimated at approximately 330 square meters (22 meters long and 15 meters wide) (Al-Shaery et al, 2022), further intensifies the concentration of worshippers within the designated space.

The prayer in Al-Rawdah carries immense reward, and all Muslims aspire to perform their prayers there, seeking tranquility, serenity, and a profound connection with Allah. The ambiance of faith created during these prayers is unforgettable. This objective poses a significant challenge in creating a comprehensive system that meets all these requirements for visitors amidst the large crowds flocking to the Prophet's Mosque. Therefore, this scholarly paper will explore the development of a comprehensive system that meets the needs of visitors (pilgrims) to Al-Rawdah, ensuring that all necessary facilities for prayer are provided, thereby making the journey a spiritual experience characterized by tranquility and peace.

2. Literature Review

Several researchers have explored crowd-management strategies for religious sites. The study by Haghani et al. (2023) investigated crowd control measures at the Grand Mosque in Mecca, emphasizing the use of real-time monitoring and dynamic route planning to optimize crowd flow. Similarly, studies by Al-Shaery et al. (2022) examined queue management systems at Hindu pilgrimage sites in India, highlighting the importance of efficient queuing systems and clear signage. Research by Ahmed and Amagoh (2010) and Ahmed (2021). focused on visitor experience at religious tourist destinations, emphasizing the role of service quality and infrastructure in enhancing satisfaction. These studies highlight the crucial need for data-driven approaches to manage visitor flow and enhance the pilgrim experience at religious sites.

The behavior of a crowd in normal conditions differs significantly from that during emergencies and evacuations. Crowd behavior influences visitor flow, speed, and concentration. During emergencies, individuals often lose rationality and patience, becoming anxious and panicked, which can result in stampedes and loss of life and property. Calculating and controlling speed and density are essential parameters to prevent overcrowding, which can potentially trigger emergencies. CNN-based Approach for Hajj Crowd Management: This approach proposes a Convolutional Neural Network (CNN) to analyze crowd data and predict potential bottlenecks during Hajj, highlighting the potential of artificial intelligence for real-time crowd management (Albattah et al. 2021; Khan and McLeod, 2012).

Agent-Based Method for Hajj Management: This method simulates crowd movement and decision-making processes during Hajj, providing valuable insights for virtually testing different crowd-management strategies before implementation (Alazbah and Zafar,2019). Crowd and Hajj Management encompasses various aspects, including pre-pilgrimage planning, risk mitigation, and post-pilgrimage evaluation, which help redesign Al-Rawdah's crowd management (Almutairi et al, 2022). Crowd Collaboration Simulation Framework: While not directly related to Hajj, this framework offers insights into how pilgrims might collaborate with crowd management efforts in Al-Rawdah (Yang & Sun, 2020). A Roadmap for the Future of Crowd Safety: This approach emphasizes crowd safety in crowd management, proposing a "Swiss Cheese Model" to identify and mitigate potential risks, thereby enhancing safety measures at Al-Rawdah (Haghani et al., 2023). The existing research demonstrates growing interest in using technology and simulation for crowd management at large religious gatherings. These studies provide valuable insights for optimizing crowd management at Al-Rawdah, with a focus on real-time analysis, risk mitigation, and fostering collaboration with pilgrims.

Several researchers have investigated crowd dynamics and statistics within the context of Hajj and visitation at the Prophet's Mosque in Madinah, including the development of a simulation tool that predicts peak crowd density within a specific area of the Prophet's Mosque. This study concluded that implementing a batch-wise crowd management strategy with optimized batch sizes and inter-batch timing would be beneficial (Alshehri et al 2015). Kirlangicoglu et al. utilized modeling techniques based on average pedestrian velocity to analyze crowd dynamics. They proposed developing a metro line to mitigate the impact of peak crowd seasons (Haghani et al., 2023). Haron et al. 2012) investigated crowd-evacuation strategies for scenarios in which the number of visitors reaches capacity. Their research employed a crowd evacuation simulation tool and included an analysis of potential future considerations for crowd management (Haghani et al, 2023). Researchers leveraged Global Positioning Systems (GPS) and Geographic Information Systems (GIS) technologies to analyze pedestrian movement patterns during the Tawaf ritual around the Kaaba during Hajj in 2004. This case study offers valuable insights applicable to crowd management in Medina (Haghani et al., 2023; Alamri et al., 2018; Al-Shaery et al., 2022). Visitor statistics for the Prophet's Mosque indicate that over 300,000 visitors were recorded daily during the Hajj period of 1437H (2016) (Haron et al., 2012). Saudi Vision 2030, launched in April 2016, includes a program to serve the guests of the Holy Sites. This program aims to facilitate hosting additional pilgrims and ease access to the Holy Sites. The primary strategic objective is to increase the number of Umrah visitors and visits to the Prophet's Mosque, aiming for 30 million by 2030.

Considering the importance of the Prophet's Mosque and the expected increase in visitors, this study aims to gather statistical crowd data to understand the current situation and identify the need for modifications to ensure pilgrim safety. The literature lacks a comprehensive analysis that utilizes manual statistical data collection to calculate crowd dynamics parameters using a systems design approach. This methodological study will fill this gap. Limited research on Rawdah crowd management: While there is existing research on crowd dynamics and management for the Prophet's Mosque, there is a lack of studies specifically focused on the Rawdah Sharifah. Focus on simulations: Existing studies on crowd management in the mosque rely on simulations but lack real-world data collection. The document highlights the lack of a systematic approach to collecting data on crowd movement and density in Rawdah Sharifah. The current literature does not adequately consider visitor needs, safety, and efficient crowd management within the Rawdah Sharifah.

The importance of the research is underscored by the effective crowd management at the Prophet's Mosque, particularly in the Rawdah Sharifah, which is crucial for the Saudi Arabian government in serving visitors to the Holy Mosque. This research makes a significant contribution by developing a comprehensive system that addresses visitor needs, minimizes the risk of overcrowding, and proposes effective mitigation strategies. Implementing this system can potentially achieve the vision of welcoming 30 million visitors annually.
Based on these gaps, the study focuses on the following aspects:

1) Implement a comprehensive data collection method to understand visitor flow and identify bottlenecks.
2) Develop a system design for visitation that incorporates crowd management principles and ensures a high standard of safety and spiritual experience.
3) Analyze the current process and propose recommendations for improved capacity planning and management within the Rawdah Sharifah.

Research Questions

The research aims to address research gaps by reducing average visit time while maintaining high-quality service. Here are the key questions guiding this investigation:

Qa) How effectively can a QFD incorporate visitor needs and technical requirements, optimize crowd management at Al-Rawdah, and enhance visitor experience? (This question focuses on the degree of improvement achievable using the QFD approach and its direct impact on visitor experience.)

Qb) How does applying QFD to Al-Rawdah's crowd management system impact key performance indicators (KPIs) related to visitor experience, such as waiting times, flow efficiency, and perceived safety? (This question delves deeper into the specific effects of QFD on visitor experience metrics.)

Qc) Can a QFD-based system demonstrably reduce bottlenecks and improve visitor satisfaction with crowd management compared to existing practices at Al-Rawdah? (This question introduces a comparative aspect, seeking measurable improvements over current methods.)

Subsequently, the Research Hypothesis is structured as follows:

The core hypothesis suggests significant potential for improving the quality of service during visits to Al-Rawdah by implementing crowd and quality management tools. Three hypotheses support this study:

H1) Implementing a QFD-based crowd management system at Al-Rawdah will significantly improve visitor experience metrics (waiting times, flow efficiency, perceived safety) compared to the existing system.

H2) QFD analysis will identify critical technical requirements for Al-Rawdah's crowd management system, including optimized capacity planning, real-time risk assessment, and enhanced visitor flow management, thereby reducing bottlenecks and increasing visitor satisfaction.

H3) Utilizing KPIs established through QFD analysis will enable effective monitoring and evaluation of the QFD-based system's effectiveness in improving crowd management and visitor experience at Al-Rawdah.

3. Methodology and Analysis

We use a mixed-method approach for this study. To address the research hypotheses, we proposed a process flowchart that maps the Al Rawdah Al Shareefa pilgrim journey, and we employed Quality Function Deployment (QFD; Ahmed & Amagoh, 2010) to translate pilgrim needs and expectations into measurable technical requirements. QFD is a customer-centric approach that aligns system design with user needs. It translates customer requirements into technical specifications through a series of matrices. By prioritizing customer wants and mapping them to design parameters, QFD ensures that the system meets expectations. It fosters collaboration, reduces design iterations, and improves system quality and performance.

3.1 Data collection involved two primary methods:

- Research Study Surveys: A purposive sample of 60 pilgrims is available from around the proximity of Al-Haram surrounding hotel accommodations, Dar-Al-Taqua, Radisson, Holton, and Intercontinental, Le Meridian, regarding their experiences, wait times, satisfaction levels (Table 1), time to perform the necessary rituals, and desired improvements. The required data for QFD are collected through face-to-face interviews with all stakeholders. Sections 3 and 4 provide the reader with information on the respective data-collection components. We record the average experience of a group visiting the pilgrimage area.

Table 1. Flow Process

Step	Description	Average time (minutes)	Potential Bottleneck
1	Arrival	2	N/A
2	Queue for Security Check	Variable (10-50)	High congestion during peak hours [Note: Observations are based on the pilgrim experience in a group visit]
3	Security Check	5	N/A
4	Queue for Entry	Variable (5-30)	Limited entry points [Note: Observations are based on the pilgrim experience in a group visit]
5	Entry and Directional Signage Review	2	N/A

6	Pilgrim Movement within Al Rawdah Al Shareefa	Variable (35-45)	N/A (depends on pilgrim behavior) [Note: Observations are based on pilgrim experience in a group visit]
7	Exit	Variable 2-4	N/A [Depends on the number of gates for exit operation]

• Observations: Trained researchers conducted on-site observations to assess queue lengths, pilgrim behavior, and potential safety hazards. Process flow charts revealed several bottlenecks in the pilgrim journey, including security checks, limited entry points, and inadequate directional signage. These bottlenecks contributed to long wait times and potential frustration among pilgrims.

The flowchart illustrates the typical journey of a pilgrim to Al-Rawdah Al-Sharifah. The flowchart depicts the typical journey of a pilgrim to Al Rawdah Al Shareefa. Each step represents an activity the pilgrim undertakes, and the average time spent at each step is listed. The last column identifies potential bottlenecks that contribute to longer wait times and hinder the overall flow.

1. **Arrival:** Pilgrims arrive at the designated area outside Al Rawdah Al Shareefa.
2. **Queue for Security Check:** Pilgrims wait in line for a security check. This stage experiences significant variations in waiting time (10-60 minutes) due to fluctuating visitor flow, which can lead to bottlenecks during peak hours.
3. **Security Check:** Security personnel conduct a security check on each pilgrim. This stage has a relatively stable time frame (around 5 minutes).
4. **Queue for Entry:** Pilgrims wait in line to enter Al-Rawdah Al-Sharifah. Similar to the security check queue, this stage exhibits variable wait times (5-30 minutes) due to limited entry points, which may create another bottleneck.
5. **Entry and Directional Signage Review:** Pilgrims enter Al Rawdah Al Shareefa and review directional signage to navigate the space. This stage has a short and consistent timeframe (approximately 2 minutes).
6. **Pilgrim Movement within Al Rawdah Al Shareefa:** Pilgrims move within the designated area for prayer and reflection. This stage has a variable time frame (15-45 minutes), depending on the individual pilgrim's behavior and desired length of stay.
7. **Exit:** Pilgrims exit Al Rawdah Al Shareefa. This stage has a short and consistent timeframe (approximately 2 minutes).

The parameters that are related to the process flows are discussed next.

- **Throughput Time:** the average time it takes for a pilgrim to complete the entire journey (from arrival to exit). Due to variable queue wait times, calculating a precise throughput time is challenging. However, based on the table, the minimum throughput time would be 25 minutes (the Sum of the average times), and it could potentially exceed 100 minutes depending on the queue lengths.
- **Cycle Time:** the average time it takes one unit (pilgrim) to complete a single process cycle. Like throughput time, queue variability makes it difficult to calculate an exact cycle time. However, the minimum cycle time would be 23 minutes (Average times excluding arrival and exit) and could be significantly higher with long queues.
- **Station Time refers to the average processing time at each** step (excluding queues). Table 1 shows that station times are relatively short (2-5 minutes) compared to queueing times, indicating efficient processing. The pilgrims' experience in a group serves as a source of information.
- **Bottleneck Analysis:** The identified bottlenecks are the security checkpoint capacity and the limited number of entry points. These bottlenecks contribute to the long queues in Steps 2 and 4, significantly impacting throughput and cycle times.
- The variability in queueing times highlights the need for a data-driven crowd management system to optimize visitor flow and minimize waiting times.

3.2 Observation Data

Survey data revealed long wait times (average = 61 minutes) and congestion during peak hours. Additionally, many pilgrims (68%) expressed concerns about overcrowded situations. Observations confirmed the bottlenecks identified through process flow analysis and highlighted issues such as humidification and ventilation, as well as access to ZamZam water.

Data Table and Sample Calculations
The provided data offers a glimpse of the crowd management survey results for mass crowd events. A systems study is usually necessary to observe a time study at random intervals. Based on the available data and information, we present the sample calculations for illustrative purposes. The table lists data by visitor experience.

4. Data and QFD Analysis

Quality Function Deployment, or QFD, is a structured method that translates customer needs, CRs, or the "Voice of the Customer, VOC" into technical requirements, also called technical requirements or TRs. It also refers to engineering needs, Ahmed and Amagoh (2010), and Ahmed (2021). It ensures that a service offering aligns with visitor expectations at Al Rawdah Al Sharifa. It identifies essential pilgrim requirements, weights, and corresponding technical requirements with detailed specifications.

Table 2. QFD Matrix for Al Rawdah Al Sharifa:

Customer Requirements (VOC)	Weight	Technical Requirements	Correlation Strength
Minimize wait times (checkpoints)	High	Increase staffing during peak hours	Strong
Minimize wait times (entry)	High	Implement a virtual queuing system	Strong
Minimize wait times (prayer)	High	Optimize prayer area layout	Medium
Minimize wait times (exit)	Medium	Review checkpoint procedures	Medium
Manage visitor flow	Medium	Improve signage for visitor flow	Medium
Ensure appropriate capacity	High	Define capacity limits for different times	Strong
Open during important times	High	Extend hours during Ramadan	Strong
Cleanliness and amenities	Medium	Increase cleaning frequency	Medium
Informative communication	Medium	Update the website with real-time wait times	Medium

Customer Requirements (CRs) and Specifications (VOC):
The potential customer requirements and specifications:

- **Wait Times:**
  - Requirement: Minimize wait times throughout the visit process (including checkpoints, entry, prayer, and exit).
  - Specification: Maximum acceptable wait time for each stage (e.g., security check < 10 minutes).
  - KPI: Average wait time per stage, % of visitors waiting within specified time limits.
- **Capacity Management:**
  - Requirement: Manage visitor flow to avoid overcrowding (Haghani et al., 2023)
  - Specification: Define appropriate capacity limits for different times (day, season).
  - KPI: Visitor density per area, compliance with capacity limits.
- **Time Importance:**
  - Requirement: Ensure access during high-impact periods for visitors (e.g., Ramadan).
  - Specification: Extended opening hours during specific periods.
  - KPI: Percentage of visitors satisfied with opening hours.
- **Additional Considerations:**
  - Amenities (cleanliness, washrooms, prayer facilities)
  - Information availability (wait times, crowd levels)
  - Respectful and courteous staff

Technical Requirements (TRs) and Specifications:
These are engineering solutions that address customer requirements:

- **Staffing:**
    - Requirement: Adjust staffing levels based on anticipated visitor volume.
    - Specification: Increased staff during peak hours and seasons.
    - KPI: Staff-to-visitor ratio during different periods.
- **Queue Management:**
    - Requirement: Implement a system to manage queues efficiently.
    - Specification: Virtual queuing system or designated queuing areas.
    - KPI: Queue length, waiting time variability.
- **Facility Design:**
    - Requirement: Optimize space allocation for smooth visitor flow.
    - Specification: Review and improve checkpoint layouts or designated prayer areas.
    - KPI: Time spent navigating different sections of the site.
- **Communication:**
    - Requirement: Provide clear and timely information to visitors.
    - Specification: Signage displaying wait times, announcements, and website updates.
    - KPI: Visitor awareness of wait times and procedures.

4.1 Identify Relationships and Prioritize Actions:

The HOQ (House of Quality (Ahmed and Amagoh, 2010; Ahmed, 2021) helps identify strong relationships between CRs (customer requirements) and TRs (technical requirements) (Refer to section 4, "Data and QFD Analysis,**" and Table 2**). These connections highlight which technical improvements will have the most significant impact on meeting customer needs (Ahmed and Amagoh, 2010; Ahmed, 2021). We utilize data and inferential statistical analysis to prioritize actions and allocate resources for improvement initiatives.

This QFD matrix helps prioritize actions based on customer needs and their relationship with achievable technical solutions. For example, minimizing wait times at checkpoints and during entry strongly correlates with increased staffing and implementing a virtual queuing system. These solutions should be prioritized, as they significantly impact the ability to address critical customer needs.

Table 3. Survey Results - Waiting Times (minutes)

Time	Min	Max	Average	Standard Deviation
Morning	3	60	18	15.61
Afternoon	2	60	18	16.10
After Asr	5	60	13	6.24
After Isha	3	120	61	30.56
Midnight	5	90	29	24.39*

The Midnight and After Isha data have a high standard deviation [Table 3] due to outliers*. While the provided data allows for descriptive analysis, inferential statistical tests support the sample size and survey design. However, some observations are essential to note:

- **Average Waiting Times:** The average waiting times across all shifts (Table 3) suggest a statistically significant difference from the ideal of 30 minutes mentioned in Table 5 (Waiting Time & Sequence).
- **Standard Deviations:** The high standard deviations in waiting times for most periods (Table 3) indicate variability in visitor flow, potentially due to a lack of crowd management strategies.

We use a portion of the sample data to demonstrate the suggested algorithm, highlighting its computational sequence. The research makes a unique contribution to event and crowd management in mega events, and it will have more significant ramifications for robust system design to manage crowds safely and securely.

4.2 Algorithm:

1. **Rank Weight Time (Calculated):**
    - Assign a weight to wait time based on its rank. Higher ranks (with longer wait times) receive a higher weight.

   - Compute: Rank Weight Time = Wait Time (Minutes) * Rank (Wait Time)
   - **Example:** Visitor 1: Rank Weight Time = 3 minutes * Rank (Wait Time) 5 = 15
2. **Rank (Wait Time) (Calculated):**
   - Assign each visitor a rank (position) based on their wait time, with the visitor with the longest wait time receiving Rank 1.
   - **Method:** Sort the wait times in descending order and assign corresponding ranks (1 for highest, 5 for lowest in this case).
   - **Compute:** Visitor 2 has the highest wait time (30 minutes) and therefore gets Rank 1.
3. **Rank (Satisfaction [Table 5]) (Calculated):**
   - Like Rank (Wait Time), this assigns a rank to each visitor based on their satisfaction rating, with the highest rating (most satisfied) getting Rank 1.
   - **Compute:** Sort the satisfaction ratings in descending order and assign corresponding ranks (1 for highest, 5 for lowest).
   - **Example:** Visitor 4 has the highest satisfaction rating (5) and therefore gets Rank 1.
4. **Difference in Ranks**
   - Find the difference between the rank in wait time and satisfaction rating. A positive value indicates the visitor waited longer than their satisfaction rank suggests.
   - Compute: Difference in Ranks = Rank (Wait time) - Rank (Satisfaction)
   - **Example:** Visitor 1: Difference in Ranks = Rank (Wait time) 5 - Rank (Satisfaction) 3 = 2
5. **Squared Difference (Calculated):**
   - Compute the squares of the rank differences to emphasize more significant discrepancies.
   - Find: Squared Difference = (Difference in Ranks) ^ 2
   - **Example:** Visitor 1: Squared Difference = (Difference in Ranks) 2 ^ 2 = 4
6. **Rank Satisfaction**
   - Calculate the total and overall score by totalling the squared differences for all visitors and dividing by the total number of visitors: Rank satisfaction = Σ (Squared Difference) / Total Visitors.

Rank Satisfaction: We compute the "Rank Satisfaction" score as shown below:
Total Squared Difference = 4 + 16 + 4 + 4 + 4 = 32 Total Visitors = 5
Rank Satisfaction = 32 / 5 = 6.40
Scale and Data Collection:

- **Wait Time:** Likely in minutes.
- **Satisfaction Rating:** Assumed to be on a scale of 1 (least satisfied) to 5 (most satisfied).
- **Data Collection:**
   - Wait Time: Gathered through website tracking or manual recording.
   - Satisfaction Rating: Obtained through a survey (scale assumed to be 1-5).

4.3 Analysis of Wait Time and Satisfaction Rating

The following section summarizes the analysis of wait time and satisfaction rating, including Spearman's Rank Correlation Coefficient (rho) and other metrics [Table 4].

Calculation of Spearman's Rank Correlation (rho):

1. **Rank the data:** Sort wait time and satisfaction rating separately in descending order, and assign ranks (1 being the highest).

Table 4. Spearman's Rank Correlation

Visitor ID	Wait Time	Rank (Wait Time)	Satisfaction Rating	Rank (Satisfaction)	Difference in Ranks (d)	d^2
1	3	5	4	3	2	4
2	30	1	2	5	-4	16
3	20	2	3	4	-2	4
4	15	3	5	1	2	4
5	10	4	4	2	2	4

2. **Calculate the squared difference (d^2) for each visitor.**

3. **Sum the squared differences (Σd^2)**: $\Sigma d^2 = 4 + 16 + 4 + 4 + 4 = 32$
4. **Calculate the number of visitors (n)**: $n = 5$
5. **Apply the formula**: $rho = 1 - [(6 * \Sigma d^2)] / (n * (n^2 - 1))$

$rho = 1 - [(6 * 32)] / (5 * (5^2 - 1)) = -0.60$

Table 5. Satisfaction Rating

Metric	Formula	Data	Interpretation
Spearman's Rank Correlation (rho)	$1 - [(6 * \Sigma d^2)] / (n * (n^2 - 1))$	rho = -0.60	Moderate negative correlation. Longer wait times tend to be associated with lower satisfaction ratings, but the relationship is moderate.
Mean Satisfaction Rating	Σ Satisfaction Rating / Number of Visitors	Mean = 3.60	Visitors are somewhat satisfied on average (assuming a scale of 1-5).
RMSE (Difference in Ranks)	$\sqrt{[\Sigma (\text{Difference in Ranks})^2 / \text{Number of Visitors}]}$	RMSE = 2.53	There are moderate differences in the ranks of wait time and satisfaction rating for each visitor.

5. Conclusion

This research makes a novel contribution to the field of event and crowd management in the context of significant events, and it is likely to impact the creation of resilient systems significantly focused on maintaining safety and security during crowd management. The analysis of the pilgrim journey at Al-Rawdah Al-Shareefa identified bottlenecks and inefficiencies within the current process. The results suggest a persistent need to enhance visitor flow management at Al Rawdah Al Shareefa. Implementing professional crowd management strategies informed by real-time data can optimize visitor flow and minimize wait times. Integrating advanced technologies, such as queue-monitoring systems, could further enhance operational efficiency. Determining the optimal visitor capacity for Al Rawdah Al Shareefa is crucial for ensuring safety and a comfortable experience. This determination should consider space limitations, ventilation capacity, and emergency protocols. Furthermore, we present the critical findings along with quantified results.

- **Bottlenecks:** Security checkpoints and limited entry points were significant bottlenecks. The process flow chart (Table 1) revealed average wait times of 10 to 50 minutes at security checkpoints and 5 to 30 minutes at entry points. The wait times exceed the desired threshold, creating discomfort among pilgrims. The data records the pilgrim group experience.
- **Variable Wait Times:** Data from Table 3 showed significant variability in wait times across different stages:
  - Morning (average wait time: 18 minutes)
  - Afternoon (average wait time: 18 minutes)
  - After Asr (average wait time: 13 minutes)
  - After Isha (average wait time: 61 minutes)
  - Midnight (average wait time: 29 minutes)

High wait-time standard deviations across most periods (Table 3) indicated inconsistent visitor flow, likely due to a lack of crowd management strategies.

- **Survey Results:**
  - The research study survey revealed an average wait time of 61 minutes. It exceeds the 30-minute ideal mentioned in Table 5 (Waiting Time & Sequence).
  - 68% of pilgrims expressed concerns about overcrowded situations, highlighting a need for improved capacity management.

These quantitative results underscore the need for implementing a data-driven crowd management system to optimize wait times and provide a more comfortable pilgrim experience.

This research investigates the synergistic application of "Quality-Function-Deployment" (QFD) and "House-of-Quality" (HoQ) for optimizing the integration of public facility systems by mapping customer requirements to technical specifications (Ahmed and Amagoh, 2010; Ahmed, 2021). The QFD and HoQ facilitate a holistic approach, Ahmed and Amagoh (2010) and Ahmed (2021). This research advances public facility design methodologies by providing a structured and comprehensive approach to achieving optimal system integration.

5.1 Results Supporting QFD Hypothesis for Systems Design

The research suggests that a QFD is valuable for optimizing crowd management at Al-Rawdah Al-Shareefa. Here's how the findings support this approach:

- **Customer Needs Translating into Technical Requirements:** The QFD enables translating customer needs (e.g., shorter wait times, reduced congestion) (Haghani et al., 2023; Alamri et al., 2018; Al-Shaery et al., 2022). into specific technical requirements (e.g., increased staffing during peak hours, virtual queuing systems).
- **Prioritization based on Impact:** We can prioritize actions based on the strength of the correlation between visitor needs and achievable technical solutions. For instance, addressing bottlenecks at security checkpoints by increasing staffing during peak hours (a strong correlation) would likely yield a significant positive impact on wait times.
- **Data-Driven Approach:** The QFD refines system design based on data from real-time queue-monitoring systems and visitor feedback surveys. This data enables measuring the effectiveness of implemented solutions and identifying areas for further improvement.

The QFD design is a structured and data-driven approach to improve crowd management at Al-Rawdah Al-Shareefa. It addressed bottlenecks and wait-time issues. The research makes a unique contribution to the domain of event and crowd management for mega-events and is expected to yield significant outcomes for developing comprehensive systems focused on maintaining safety and security.

References

Ahmed, Q., and Memish, Z. A., From the "madding crowd" to mass gatherings—religion, sport, culture and public health. *Travel Medicine and Infectious Disease*, 28, 91–97, 2019.

Ahmed, S., A hybrid methodology for dental hospital quality performance gap using HOQ and process analysis. *International Journal of Service Science, Management, Engineering and Technology*, 12(6), 16–42, 2021.

Ahmed, S., and Amagoh, F., Application of QFD in product development of a glass manufacturing company in Kazakhstan. *Benchmarking: An International Journal*, 17(1/2), 195–213, 2010. https://doi.org/10.1108/14635771011036302

Alamri, R. J., Alkhuriji, M. S., Alshamani, M. S., Ibrahim, O. Y., and Haron, F., Al-Masjid An-Nabawi crowd adviser crowd level estimation using head detection. In *Proceedings of the 2018 1st International Conference on Computer Applications and Information Security (ICCAIS)* (pp. 1–4). IEEE, 2018.

Alazbah, A., and Zafar, B. A., Pilgrimage (Hajj) crowd management using agent-based method. *International Journal on Foundations of Computer Science & Technology*, 9(1), 1–17, 2019.

Albattah, W., Khel, M. H. K., Habib, S., Islam, M., Khan, S., et al., Hajj crowd management using CNN-based approach. *Computers, Materials & Continua*, 66(2), 2183–2197, 2021. https://doi.org/10.32604/cmc.2020.014227

Almutairi, M. M., Apostolopoulou, D., Halikias, G. D., Abi Sen, A. A., and Yamin, M., A framework for comprehensive crowd and Hajj management. In *Proceedings of the 2022 9th International Conference on Computing for Sustainable Global Development (INDIACom)* (pp. 63–68). IEEE, 2022. https://doi.org/10.23919/INDIACom54597.2022.9763174

Al-Shaery, A. M., Aljassmi, H., Ahmed, S. G., Farooqi, N. S., Al-Hawsawi, A. N., Moussa, M., Tridane, A., and Alam, M. D., Real-time pilgrims management using wearable physiological sensors, mobile technology, and artificial intelligence. *IEEE Access*, 10, 120891–120900, 2022.

Alshehri, A., Muhammad, A., Alkhemi, M. M., and Felemban, E., Analysis of crowd movement in the Prophet (SAW) Mosque in the city of Madinah, Saudi Arabia. In *Proceedings of the Third International Conference on Advances in Computing, Electronics and Electrical Technology* (pp. 151–160), 2015.

Haghani, M., Coughlan, M., Crabb, B., Dierickx, A., Feliciani, C., Gelder, R., et al., A roadmap for the future of crowd safety research and practice: Introducing the Swiss Cheese Model of Crowd Safety and the imperative of a Vision Zero target. *Safety Science*, 168, 106292, 2023. https://doi.org/10.1016/j.ssci.2023.106292

Haron, F., Alginahi, Y. M., Kabir, M. N., and Mohamed, A. I., Software evaluation for crowd evacuation – case study: Al-Masjid an-Nabawi. *International Journal of Computer Science Issues*, 9(6/2), 128–134, 2012.

Khan, I., and Mcleod, R. D., Managing Hajj crowd complexity: Superior throughput, satisfaction, health, and safety. *Arabian Journal of Business and Management Review (Kuwait Chapter)*, 33(853), 1–15, 2012.

Sahih al-Bukhari, Book 60, Hadith 430.

Yang, R., and Sun, H., A new simulation framework for crowd collaborations. *International Journal of Crowd Science*, Advance online publication, 2020. https://doi.org/10.1108/IJCS-02-2020-0006

Biography

Professor Shamsuddin Ahmed is an accomplished industrial engineer with over 25 years of global experience spanning academia, research, consulting, and entrepreneurship. He holds a Ph.D. in Operations Research from Edith Cowan University, Australia, and an MASc in Industrial Engineering from Dalhousie University, Canada. He has held professorial and leadership roles at institutions including the Islamic University of Madinah (Current), NMIMS Mumbai, and KIMEP Kazakhstan. His research expertise covers supply chain management, operations research, financial engineering, risk management, and AI applications, with over 50 publications in ISI/Scopus-ranked journals. He has secured more than USD $200,000 in research funding and led high-impact consulting projects, including a SAR 41 million cost-saving initiative for IUM's university canteen. A recipient of multiple "Best Research" awards and the 2024 "Incredible Researcher of the World" honor, he has also founded successful startups and developed industry-standard software tools in simulation, Six Sigma, and enterprise risk management.