The 24th Scientific Forum for Hajj, Umrah and Visit Research

Excellence in Transportation and Mass Gatherings Management

UMM AL-QURA UNIVERSITY

The Custodian of the Two Holy Mosques Institute for Hajj and Umrah Research

The scientific bulletin of

The 24th Scientific Forum for Hajj, Umrah and Visit Research

Under the theme

Excellence in Transportation and Mass Gatherings Management

Organized by

The Custodian of the Two Holy Mosques Institute for Hajj and Umrah Research

Umm Al-Qura University

Under the Generous Patronage of the Custodian of the two Holy Mosques

King Salman bin Abdulaziz Al Saud

(may Allah protect him)

The Scientific Bulletin

The 24th Scientific Forum for Hajj, Umrah and Visit Research in Umm Al-Qura University

Under the theme

Excellence in Transportation and Mass Gatherings Management

The 24th Scientific Forum for Hajj, Umrah and Madinah Visit Research

The Scientific Bulletin

English Part

Preface

Under the Patronage of the Custodian of the Two Holy Mosques, King Salman bin Abdulaziz Al Saud (may Allah protect him), the 24th Scientific Forum on Hajj, Umrah, and Visit Research Organized by the Custodian of the Two Holy Mosques Institute for Hajj and Umrah Research, Umm Al-Qura University, under the Theme: "Excellence in Transportation and Mass Gatherings Management" in Makkah. This forum is held annually, alternating between Makkah and Madinah. It serves as an annual scientific event and a platform where experts, officials, and practitioners in the fields of Hajj, Umrah, and visit convene to present their research, studies, and proposals. It fosters the exchange of ideas and leverages the latest global technologies and scientific advancements to continuously enhance the services provided to pilgrims and visitors of the Two Holy Mosques. The forum underscores the importance of utilizing beneficial knowledge and good practices in serving the Two Holy Mosques. The forum seeks to engage specialized researchers from Saudi universities and research institutes, alongside individuals interested in Hajj, Umrah, and visit studies. It also invites participants from government agencies, the private sector, and the third sector to present their original research papers within the themes of this year's forum (1446 AH), which include: Strategic Planning in Transportation and Mass Gatherings Management, Promoting Health and Safety in Mass Gatherings Management, Modern Systems and Technologies in Transportation and Mass Gatherings Management, and Sustainable Practices in Transportation and Mass Gatherings Management. The scientific committee received approximately 172 research abstracts from more than 49 academics, governmental, private, and third-sector entities. These submissions were peer-reviewed by experts and specialists, resulting in the selection of 58 topics, including scientific papers and working papers. This scientific record comprises around 35 scientific papers, while the forum's website features scientific posters for the working papers. On this occasion, the scientific committee expresses its deep gratitude to the researchers who shared their work and ideas with the forum, as well as to the specialized reviewers from various colleges and experienced experts, at the Custodian of the Two Holy Mosques Institute for Hajj and Umrah Research, who evaluated and reviewed the submitted work. Their efforts greatly assisted the committee in making decisions regarding the acceptance of scientific contributions. The committee also extends heartfelt thanks to everyone who provided scientific, financial, or moral support, particularly His Excellency the Minister of Education, the esteemed President of the University, and the Dean of the Custodian of the Two Holy Mosques Institute for Hajj and Umrah Research, who chairs the organizing committee of the forum.

The Scientific Committee of the 24th Scientific Forum on
Hajj, Umrah and Visit Research

The Scientific Committee of the 24th Scientific Forum of Hajj, Umrah and Madinah Visit Research

The Custodian of the Two Holy Mosques Institute for Hajj and Umrah Research – Umm Al-Qura University

9-10 Jumada al-Akhirah 1446 AH corresponding to 10-11 December 2024

Email: (multaqa@uqu.edu.sa)

Electronic portal: (hajj.uqu.edu.sa/multaqa)

P.O. 6287 - Postal code: 21955, Makkah

The main Scientific Committee of the 24th Scientific Forum on Hajj, Umrah, and Visit Research

Chairman of the Committee	Dr. Adnan Y. Alshahrani
Committee members	Prof. Khalid A. Alghamdi
	Dr. Abdullah A. Bagasi
	Dr. Olfat M. Mirza
	Dr. Abdullah A. Alnabati
	Dr. Majid A. Bamaga
	Dr. Abdullah N. Al hawsawi
	Prof. Hamdy M. Youssef
	Prof. Emad A. Felemban
	Dr. Khalid A. Osra
	Dr. Ahmed K. Alqurashi
	Dr. Mohannad A. Alyamani
	Dr. Mohammed A. Garout
	Dr. Ahmad H. Metair
	Naif M. Bashraf
	Razaz H. Qabbani

The Scientific Subcommittee of the 24th Scientific Forum for Hajj, Hajj, Umrah and Visit Research

Chairman of the Committee	Dr. Khalid A. Osra
Committee members	Dr. Ahmed M. Kabli
	Prof. Fathy F. Shaaban
	Prof. Omar B. Ahmed
	Prof. Ayman M. Mostafa
	Dr. Waleed A. Abou El Saoud
	Dr. Ahmed Mohamed HelalY
	Dr. Mohamed S. Yasein
	Ibtisam M Hadyan

Key speakers at the sessions of the 24th Scientific Forum for Hajj, Umrah and Visit Research

1st Session	The Theme of Strategic planning in Transportation and Mass Gatherings Management
Key Speaker	**Major General Dr. Mohammed bin Abdullah Al-Qarni** General Supervisor of the Pilgrimage Management and Joint Operations Center

Major General Dr. Mohammed A Al-Qarni is a PhD holder in sociology. He participated in more than 100 media and press meetings regarding Hajj work, civil defense work, and pilgrims transport work. He participated in more than 90 workshops to develop projects in Makkah and the Holy Sites during Hajj event, which for more than forty years' experience in leadership participation in the field.

1nd Session	The Theme of Strategic planning in Transportation and Mass Gatherings Management
Keynote Speaker	**Professor Omaimah Bamasag** Transport enablement agent at the General Transport Authority

Professor Omaimah Bamasag is a researcher and expert in cybersecurity and mobility systems. She is a pioneer in women's empowerment and leadership in the transportation sector, serving as the first Deputy of Transportation Enablement at the Transportation General Authority. Her research focuses on autonomous mobility, IoT, AI, and smart mobility solutions

5th Session	The Theme of Modern Systems and Technologies in Transportation and Mass Gatherings Management
Keynote Speaker	**Dr. Nasser AL-Meshary** Vice President for Strategic Partnerships and Alliances at Elm Company

Dr. Nasser AL-Meshary, Vice President for Strategic Partnerships and Alliances at Elm Company, A seasoned leader with over 25 years of extensive experience in digital transformation, smart city solutions, data analytics, and emerging technologies such as the Internet of Things (IoT), cybersecurity, blockchain, and generative AI. He has played an active role in developing business strategies, achieving sustainable financial growth, and expanding government markets

Table of Contents

Theme of Strategic Planning in Transportation and Mass Gatherings Management

A Roadmap for Implementing Urban Digital Twin to Optimise Crowd Management During Hajj

Mohammad H. Alabbasi

Urban and Engineering Department, Umm Al-Qura University.

*Corresponding author: E-mail (mhabbasi@uqu.edu.sa)

خارطة طريق لتطبيق التوأم الرقمي الحضري لتحسين إدارة الحشود أثناء الحج

محمد بن حمزة العباسي

قسم البحوث العمرانية والهندسية، جامعة أم القرى

Abstract

The Hajj pilgrimage annually brings over two million pilgrims to Mecca, creating significant challenges in crowd management and infrastructure coordination due to the event's high-density environment. Current management strategies are predominantly reactive, lacking the predictive capabilities needed to address overcrowding and resource strain proactively, which poses safety risks and logistical inefficiencies. This paper proposes an Urban Digital Twin (UDT) framework as a proactive decision support system designed to optimise crowd flow, infrastructure utilization, and emergency response during Hajj.

By integrating real-time data from IoT sensors, GPS tracking, closed-circuit television (CCTV) systems, and transportation networks into a dynamic digital model of critical Hajj sites, UDT employs predictive algorithms and Agent-Based Modelling to simulate crowd behaviors and infrastructure performance. This enables authorities to monitor crowd movements, anticipate risks, and optimize resource allocation in real time. The framework addresses technical challenges related to data integration and system scalability, as well as ethical considerations concerning data privacy and cultural sensitivities within the religious context of Hajj.

The proposed UDT framework shifts crowd management from reactive interventions to a proactive, data-driven strategy, providing decision-makers with a flexible and responsive tool to enhance safety and efficiency during the pilgrimage. By outlining a comprehensive methodology for implementation, this study demonstrates the potential of UDT technology to transform the management of large-scale events, offering insights that can be extended to similar high-density gatherings worldwide. This research is expected to significantly contribute to safer and more efficient crowd management practices during the Hajj by providing a scalable and adaptable UDT framework. The anticipated improvements in safety and efficiency not only benefit the Hajj but also offer a model applicable to similar high-density events worldwide, setting new standards for the application of digital twin technology in large-scale event planning and execution.

Keywords: Urban Digital Twin, Crowd Management, Smart cities.

1. Introduction

The Hajj pilgrimage to Mecca, is one of the largest annual religious gatherings in the world, drawing over two million Muslims from diverse cultural and geographical backgrounds. This sacred journey, a pillar of Islamic faith, transforms the city of Mecca into a densely populated hub within a remarkably short period. The influx of pilgrims presents significant challenges in crowd management, logistical coordination, and public safety. Ensuring the safe and efficient movement of such a vast number of people through a series of ritual sites over a few days requires meticulous planning and sophisticated infrastructure.

Despite continuous efforts and substantial investments by Saudi authorities to enhance infrastructure and implement advanced surveillance systems, crowd-related incidents have occurred. The tragic stampede in Mina during the 2015 Hajj, which resulted in the loss of over 700 lives, highlighted the limitations of existing crowd management strategies (Shirazi et al., 2016). Traditional approaches have predominantly relied on reactive measures, such as monitoring through closed-circuit television (CCTV) and deploying security personnel to manage crowds manually. While these methods provide a degree of oversight, they lack the predictive capabilities necessary to anticipate and prevent critical situations in real time.

Emerging technologies offer new avenues for enhancing crowd management during high-density events like Hajj. Among these, the concept of the Urban Digital Twin (UDT) has gained significant attention in the field of urban planning and smart city development. A UDT is a virtual replica of a physical urban environment, integrating real-time data from various sources—including Internet of Things (IoT) sensors, GPS devices, and infrastructure systems—into a dynamic digital model (Batty, 2018). This digital representation enables continuous monitoring, simulation, and analysis of urban processes, providing decision-makers with actionable insights.

Implementing a UDT for the Hajj crowd management could revolutionise how authorities manage crowds and resources. By simulating crowd movements and predicting potential congestion points, a UDT can facilitate proactive interventions to mitigate risks. For example, predictive modelling can optimize transportation schedules and routes, ensuring an even distribution of pilgrims across different sites and times. Integrating infrastructure data into the UDT allows for real-time monitoring of utilities such as water and electricity, preventing outages and ensuring that essential services meet the fluctuating demands during the pilgrimage.

However, the application of UDT technology in the context of Hajj is not without challenges. Technical hurdles include integrating diverse data sources, ensuring data accuracy, and processing vast amounts of information in real time. Ethical considerations are also paramount, particularly concerning the privacy of pilgrims and the handling of sensitive data. The cultural and religious significance of Hajj necessitates a careful balance between leveraging technology for safety and respecting the sanctity of the pilgrimage experience.

This study aimed to develop a comprehensive framework for implementing an Urban Digital Twin as a decision support system to optimize crowd management during the Hajj. By harnessing real-time data and predictive modelling, the proposed UDT will enable authorities to monitor crowd movements proactively, anticipate potential risks, and optimize infrastructure utilization to enhance safety and efficiency.

Despite the potential benefits of UDT technology, its application in managing large-scale, transient events like Hajj remains underexplored. Existing literature predominantly focuses on the use of UDTs in stable urban environments for purposes such as infrastructure maintenance, energy management, and traffic optimization (Dembski et al., 2020). There

is a lack of research addressing how UDTs can be tailored to high-density, event-specific scenarios characterized by highly dynamic crowd behaviors. This gap highlights the need for a specialized framework that can adapt the principles of UDT technology to the unique challenges presented by the Hajj by addressing the following research questions:

1. How can an Urban Digital Twin framework be developed to predict and manage crowd movements during the Hajj in real time?
2. How can the integration of real-time infrastructure data within a UDT framework improve resource coordination and management during Hajj?
3. What are the technical and ethical challenges in implementing a UDT framework for large-scale event management, and how can these challenges be addressed?

By addressing these questions, the research may contribute a novel approach to crowd management that leverages advanced technological solutions. The proposed framework intends to provide decision-makers with the tools necessary to transition from reactive to proactive management strategies, ensuring a safer and more fulfilling experience for millions of pilgrims.

To achieve this aim, the primary objective of this research is to develop an Urban Digital Twin (UDT) framework that significantly enhances crowd management during the Hajj. The measurable goals include:

- **Improving Travel Times**: Reduce average travel times between key pilgrimage sites by **20%** through optimised routing and scheduling.
- **Reducing Crowd Congestion**: Decrease peak crowd densities at critical locations by **30%**, minimising the risk of incidents such as stampedes.
- **Enhancing Response Times**: Shorten response times to emerging crowd-related issues by **40%** by providing real-time data and predictive analytics to decision-makers.
- **Minimising Incidents**: Reduce the number of crowd-related accidents and incidents by **25%** through proactive management and timely interventions.

2. Background and Literature Review

2.1 Challenges of Crowd Management during Hajj

The Hajj is an unparalleled event in terms of scale and complexity, attracting over two million pilgrims annually to the holy city of Mecca (General Authority for Statistics, 2019). This massive congregation occurs within a confined geographical area over a short period, leading to extreme crowd densities that pose significant risks to safety, security, and logistical efficiency (Alamoudi et al., 2020). The rituals performed during Hajj require pilgrims to move between specific sites, such as Mina, Arafat, and Muzdalifah, often simultaneously, which amplifies the challenges of managing crowd flow and preventing congestion.

Historically, crowd management during Hajj has faced several incidents that underscore the gravity of these challenges. Notably, the 2015 Mina stampede resulted in the deaths of over 700 pilgrims and injuries to hundreds more (Yamin et al., 2019). Investigations into such incidents have highlighted factors such as bottleneck formations, sudden surges in crowd movement, and insufficient real-time information as critical contributors to crowd disasters (Shirazi et al., 2016).

Traditional crowd management approaches have relied heavily on physical infrastructure enhancements and manual monitoring. Measures include expanding pathways, constructing multi-level bridges like the Jamarat Bridge to disperse crowds, and deploying thousands of security personnel to manage pilgrim movements (Memish et al., 2016). While these efforts have improved certain aspects of crowd control, they are predominantly reactive and lack the ability to predict and prevent incidents before they occur.

The limitations of current strategies are further compounded by the transient and dynamic nature of the pilgrimage population. Pilgrims come from diverse cultural backgrounds, speaking different languages and possessing varying levels of familiarity with the rituals and geography of the holy sites (Eid et al., 2020). This diversity necessitates sophisticated management systems that can adapt to real-time changes and provide guidance that transcends language barriers.

2.2 Urban Digital Twin Technology as a Solution

UDT technology has emerged as a cutting-edge solution in urban planning and smart city initiatives. A UDT is a virtual replica of a physical urban environment that integrates real-time data from multiple sources to create a dynamic, interactive model (Batty, 2018). This digital representation enables continuous monitoring, simulation, and analysis of urban systems, facilitating informed decision-making and proactive management.

The concept of digital twins originated in the manufacturing industry, where virtual models of products and processes are used to optimize performance and predict maintenance needs (Tao et al., 2019). In recent years, the application of digital twin technology has expanded to encompass entire cities and urban regions. For example, Singapore has developed "Virtual Singapore," a comprehensive 3D city model that supports urban planning, environmental modelling, and public engagement (Sun et al., 2016).

In the context of Hajj, implementing a UDT can revolutionise crowd management by providing authorities with a holistic view of pilgrim movements and infrastructure usage. By integrating data from IoT devices, GPS trackers, CCTV feeds, and other sensors, a UDT can simulate crowd dynamics and predict potential congestion points (Lu et al., 2020). This predictive capability enables authorities to implement preventive measures, such as redirecting flows or adjusting transportation schedules, before issues escalate into critical situations.

Recent applications of digital twin technology in large-scale events further demonstrate its potential. For instance, the Tokyo 2020 Olympics utilised a digital twin to manage crowd movements, transportation, and security, resulting in a seamless experience for attendees despite the challenges posed by the COVID-19 pandemic (Jones et al., 2021). Similarly, Smith and Lee (2022) explored the use of digital twins in managing crowd safety at major music festivals, highlighting improvements in emergency response times and resource allocation. These case studies underscore the versatility of UDTs in various contexts and provide valuable insights that can be adapted to the Hajj.

2.3 Real-Time Data Integration for Proactive Crowd Management

The integration of real-time data is fundamental to the effectiveness of a UDT in managing crowds during Hajj. Various technologies contribute to this data ecosystem:

- **IoT Sensors and GPS Tracking:** Wearable devices and smartphones equipped with GPS can provide anonymized location data, enabling the tracking of crowd densities and movement patterns (Kamel Boulos & Yang, 2018). This data helps in identifying hotspots and predicting where and when congestion might occur.

- **CCTV Systems and Video Analytics:** Advanced video processing algorithms can analyze CCTV footage to estimate crowd densities and detect unusual behaviours (Zhang et al., 2019). Machine learning techniques enhance the accuracy of these analyses, even in challenging conditions like low light or high crowd densities.
- **Transportation Network Data:** Real-time information from buses, trains, and other transportation services allows for the monitoring of system capacities and passenger loads (Zheng et al., 2020). Integrating this data helps in synchronizing transportation services with crowd movements.
- **Environmental Sensors:** Data on weather conditions, air quality, and other environmental factors can influence crowd behavior and health risks (Li et al., 2018). For instance, high temperatures may require adjustments in crowd management strategies to prevent heat-related illnesses.

Agent-Based Modelling (ABM) plays a crucial role in utilizing this integrated data. ABM simulates the actions and interactions of autonomous agents (in this case, pilgrims) to assess their effects on the system as a whole (Crooks & Heppenstall, 2012). By modelling individual behaviors and decision-making processes, ABM can predict how crowds will respond to various stimuli, such as route closures or schedule changes.

Studies have demonstrated the effectiveness of real-time data integration and ABM in crowd management. For example, Helbing et al. (2018) showed that predictive modelling based on real-time data could reduce evacuation times during emergencies by up to 30%. Such proactive management is essential in the high-stakes environment of Hajj, where timely interventions can prevent disasters.

2.4 UDT for Integrated Infrastructure Management

Beyond crowd movement, the Hajj exerts immense pressure on infrastructure systems, including transportation, utilities, and healthcare services. Traditional infrastructure management approaches often operate in silos, leading to inefficiencies and slow response times during peak demand periods (Xiong et al., 2020). A UDT enables the integration of these systems into a unified platform, providing a comprehensive view of resource utilization and facilitating coordinated management.

- **Transportation Optimization:** Real-time data on pilgrim movements can inform adjustments to transportation services. For instance, shuttle buses can be rerouted or their frequency increased in response to rising crowd densities in specific areas (Zhang et al., 2019). This dynamic scheduling enhances efficiency and reduces waiting times.
- **Utility Management:** Monitoring consumption patterns of water and electricity allows for proactive measures to prevent shortages or overloads. For example, temporary increases in water supply can be directed to areas experiencing high demand (Grieves & Vickers, 2017).
- **Healthcare Services:** Data on crowd densities and movement patterns can help in strategically positioning medical teams and resources. Predictive analytics can forecast potential health risks, such as heatstroke incidents during periods of high temperatures, enabling pre-emptive action (Alqurashi et al., 2019).

Integrating these systems within a UDT not only improves operational efficiency but also enhances the resilience of the entire infrastructure network. By facilitating real-time communication and coordination among different service providers, the UDT supports a more agile and effective response to emerging challenges.

2.5 Technical and Ethical Challenges

While the benefits of implementing a UDT for Hajj are substantial, several technical and ethical challenges must be addressed.

Technical Challenges:

- **Data Integration and Interoperability:** Aggregating data from diverse sources requires overcoming differences in data formats, protocols, and standards. Developing middleware solutions or adopting universal data standards can mitigate these issues (Fuller et al., 2020).
- **Scalability and Real-Time Processing:** The sheer volume of data generated during Hajj necessitates robust computational infrastructure capable of real-time processing and analysis. Cloud computing and edge computing technologies can enhance scalability and reduce latency (Chen et al., 2018).
- **Data Accuracy and Reliability:** Ensuring the quality of data is critical. Inaccurate or incomplete data can lead to flawed models and poor decision-making. Implementing data validation procedures and redundant data collection methods can improve reliability (Lu et al., 2020).

Ethical Challenges:

- **Privacy and Data Protection:** Collecting real-time data on individuals raises significant privacy concerns. There is a risk of misuse of personal information or surveillance beyond what is necessary for safety. To address this, data should be anonymized, and strict access controls should be implemented (van den Hoven et al., 2019).
- **Consent and Transparency:** Pilgrims should be informed about the data collection practices and the purposes for which their data will be used. Where possible, obtaining consent is essential, although this may be challenging given the scale and diversity of the population (Zhang & Crespi, 2020).
- **Cultural Sensitivity:** The religious significance of Hajj requires that any technological interventions respect cultural norms and practices. Technologies should be implemented in a way that does not disrupt the spiritual experience of pilgrims (Eid et al., 2020).

Addressing these challenges requires a multidisciplinary approach, involving technologists, ethicists, legal experts, and representatives from the pilgrim community. Developing a robust ethical framework and adhering to international data protection standards, such as the General Data Protection Regulation (GDPR), can help ensure that the implementation of a UDT respects individual rights and cultural values.

3. Methodology

This section outlines the development of a comprehensive framework for implementing an Urban Digital Twin (UDT) to optimize crowd management during the Hajj. The framework is designed to assist decision-makers by providing real-time insights and predictive analytics for proactive crowd control and infrastructure management.

3.1 Framework Overview

The proposed UDT framework comprises the following four key components as shown in Figure 1:

1. Data Acquisition and Integration
2. Data Processing and Modelling
3. Decision Support System and Visualization
4. Ethical and Technical Considerations

Figure 1. UDT framework's components

3.2 Data Acquisition and Integration

3.2.1 IoT Devices and GPS Tracking: Deploying IoT devices and GPS-enabled wearables will facilitate the collection of anonymized real-time location data from pilgrims (Kamel Boulos and Yang, 2018). Devices such as wristbands or smartphone applications will transmit location coordinates at regular intervals. Data privacy is ensured by anonymizing data and obtaining informed consent where feasible.

3.2.2 CCTV Systems and Video Analytics: Enhancing existing CCTV infrastructure with video analytics software enables estimation of crowd densities and detection of abnormal behaviors (Zhang *et al.*, 2019). Advanced algorithms, including convolutional neural networks, process video feeds to provide real-time assessments of crowd conditions.

3.2.3 Transportation and Infrastructure Data: Integrating data from transportation networks—such as schedules, capacities, and real-time utilization of buses and trains—allows for effective resource management (Zheng *et al.*, 2020). Infrastructure data on utilities like water and electricity consumption will be collected to monitor and manage resource utilization efficiently.

3.2.4 Environmental Sensors: Deploying environmental sensors throughout the pilgrimage sites provides data on temperature, humidity, and air quality, which can significantly impact crowd behavior and health risks (Li *et al.*, 2018). This information informs adjustments in crowd management strategies to enhance pilgrim safety and comfort.

3.2.5 Data Integration Platform: A centralized data integration platform aggregates data from all sources, ensuring interoperability through standardized data formats and communication protocols (Fuller *et al.*, 2020). Cloud-based services handle the high volume and velocity of data, ensuring scalability and reliability.

3.3 Data Processing and Modelling: Statistical and analytical techniques play a pivotal role in processing and interpreting the data collected. Predictive analytics methods such as time-series forecasting and regression analysis will be utilized to predict crowd movements and infrastructure demands (Brown and Green, 2020). Machine learning algorithms, including neural networks and clustering methods, will enhance the accuracy of crowd density estimations (White, 2019). Simulation models like Monte Carlo simulations will assess the probability of various crowd scenarios, aiding in contingency planning. These methods have been successfully applied in crowd management contexts, demonstrating their efficacy in handling complex, dynamic data environments.

3.3.1 Data Fusion and Management: Collected data undergoes preprocessing steps, including cleaning, filtering, and validation, to ensure accuracy and consistency (Chen *et al.*, 2018). Data fusion techniques combine information from different sources, enhancing overall data quality and providing a comprehensive understanding of the environment.

3.3.2 Agent-Based Modelling (ABM): ABM simulates individual pilgrim behaviors and interactions within the environment (Crooks and Heppenstall, 2012). Each agent is modelled with attributes and behavioral rules—such as movement speed, destination preferences, and responses to environmental stimuli—to predict crowd dynamics under various scenarios.

3.3.3 Predictive Analytics and Machine Learning: Machine learning algorithms analyze historical and real-time data to identify patterns and make predictions about future crowd movements and infrastructure demands (Alahi *et al.*, 2016). Techniques like time-series analysis and deep learning models forecast crowd densities, enabling proactive interventions.

3.3.4 Model Calibration and Validation: Models are calibrated using historical data from previous Hajj events to ensure accuracy (Alqurashi *et al.*, 2019). Validation involves comparing model predictions with actual observed data during pilot tests, refining parameters to improve predictive performance.

3.4 Decision Support System and Visualization

3.4.1 Real-Time Monitoring Dashboards: Interactive dashboards display real-time data visualizations, including heat maps of crowd densities, flow patterns, and infrastructure utilization (Eid *et al.*, 2020). Dashboards are customizable to meet the specific needs of different decision-makers, such as security personnel or transportation coordinators.

3.4.2 Scenario Simulation Tools: Simulation tools allow authorities to model the potential impact of various interventions, such as redirecting pedestrian traffic or adjusting transportation schedules (Zheng *et al.*, 2020). This enables assessment of strategies before implementation, reducing the risk of unintended consequences.

3.4.3 Communication and Alert Systems: Automated alert systems notify relevant stakeholders when thresholds are reached—for example, when crowd density exceeds safe levels in a particular area (Helbing *et al.*, 2018). Communication systems facilitate coordination among agencies and disseminate information to pilgrims when necessary.

3.5 Ethical and Technical Considerations

3.5.1 Data Privacy and Security: The framework prioritizes data privacy by anonymizing personal data and implementing strict access controls (van den Hoven *et al.*, 2019). Compliance with data protection regulations, such as the General Data Protection Regulation (GDPR), is ensured. Security measures, including encryption and intrusion detection systems, protect data integrity.

3.5.2 Cultural and Religious Sensitivity: Recognizing the sacred nature of Hajj, technology implementation is conducted respectfully, minimising intrusion into the spiritual experience of pilgrims (Eid *et al.*, 2020). Communication materials are developed in multiple languages to cater to the diverse population.

3.5.3 Technical Challenges and Mitigation: Challenges such as data heterogeneity, system scalability, and real-time processing demands are addressed through:

- **Standardization of Data Formats:** Adoption of open data standards facilitates interoperability (Fuller *et al.*, 2020).
- **Cloud and Edge Computing:** Utilization of cloud services for scalability and edge computing for localized data processing reduces latency (Chen *et al.*, 2018).
- **Robust Infrastructure:** Investment in high-availability systems and network redundancies ensures system reliability during peak times.

3.6 Implementation Plan

3.6.1 Pilot Deployment

A pilot program is conducted in a specific area or during a smaller-scale event to test the framework's effectiveness and identify issues (Lu *et al.*, 2020). Feedback informs adjustments before full-scale implementation.

3.6.2 Stakeholder Engagement: Collaboration with stakeholders—including government agencies, security forces, transportation authorities, and religious leaders—is essential (Alamoudi *et al.*, 2020). Regular meetings and workshops ensure alignment of objectives and facilitate knowledge sharing.

3.6.3 Training and Capacity Building: Personnel operating the UDT system receive comprehensive training on data interpretation, system functionalities, and ethical considerations (Xiong *et al.*, 2020). Capacity building extends to on-ground staff to ensure coordinated responses.

3.6.4 Evaluation and Continuous Improvement: Post-implementation evaluations assess the framework's impact on crowd management and infrastructure optimisation (Alqurashi *et al.*, 2019). Metrics such as reduction in incidents, response times, and pilgrim satisfaction guide continuous improvement efforts.

3.7 Evaluation of Model Effectiveness

To assess the effectiveness of the UDT framework compared to traditional crowd management methods, a comprehensive evaluation plan will be implemented. This plan includes:

- **Key Performance Indicators (KPIs)**: The following KPIs will be used to measure performance:
  - Average Travel Time between key pilgrimage sites.
  - Peak Crowd Density levels at critical locations.
  - Response Times to crowd-related incidents.
  - Number of Crowd-Related Accidents and Incidents.
  - Resource Utilisation Efficiency, such as transportation and utility services.
- **Comparative Study Design**: The performance of the UDT framework will be compared against historical data from previous Hajj events where traditional methods were used.
- **Data Collection Methods**:
  - **Real-Time Monitoring** using the UDT system.
  - **Historical Records** from past events for baseline comparisons.
  - **Surveys and Feedback** from pilgrims and authorities.
- **Statistical Analysis**: Statistical methods, including t-tests and ANOVA, will be employed to determine the significance of differences between the UDT framework and traditional methods.

3.8 Data Quality Assurance

Ensuring the reliability and accuracy of data is critical for the success of the UDT framework. The following measures will be implemented:

- **Data Validation Rules**: Automated checks will verify data consistency, completeness, and correctness at the point of entry.
- **Error Detection Algorithms**: Advanced algorithms will identify anomalies or outliers in the data, prompting further investigation or correction.
- **Data Governance Policies**: A formal data governance framework will define protocols for data handling, access control, and accountability.
- **Compliance with Standards**: The data quality management processes will adhere to international standards such as ISO 8000 for data quality and ISO 27001 for information security management.

4. Findings and Conclusions

The implementation of the Urban Digital Twin (UDT) framework holds significant promise in transforming crowd management and infrastructure optimization during the Hajj. By directly addressing the research questions, the anticipated outcomes suggest notable enhancements in safety, efficiency, and decision-making processes for authorities overseeing this monumental event.

Addressing Research Question 1: Developing a UDT Framework for Real-Time Crowd Prediction and Management: The proposed UDT framework effectively integrates real-time data from IoT sensors, GPS tracking, and CCTV systems to simulate and predict crowd movements during Hajj. Employing Agent-Based Modelling (ABM), the framework captures the nuanced behaviors of individual pilgrims, considering cultural and environmental factors that influence their actions. This granular level of detail allows for accurate forecasting of crowd densities in critical areas. Simulations indicate that proactive interventions informed by UDT insights—such as adjusting pedestrian flow or opening alternative routes—can substantially reduce crowd congestion. For instance, by predicting areas of potential overcrowding, authorities can implement measures to redirect pilgrims smoothly, reducing stress and enhancing their overall pilgrimage experience. This proactive approach contrasts sharply with traditional reactive methods, underscoring the framework's potential to prevent incidents like stampedes and enhance overall safety.

Addressing Research Question 2: Improving Resource Coordination through Real-Time Infrastructure Data Integration: Integrating real-time data from transportation networks and utility services into the UDT framework enables optimized resource allocation. By continuously monitoring transportation schedules, vehicle capacities, and passenger loads, authorities can dynamically adjust services to meet fluctuating demand. For example, dispatching additional buses to high-density areas or rerouting transportation to alleviate congestion becomes feasible. This optimization reduces wait times and ensures a more even distribution of pilgrims across sites. Similarly, real-time monitoring of utility usage helps prevent shortages of essential services like water and electricity. By anticipating peak demand periods, resource distribution can be adjusted proactively, ensuring uninterrupted access throughout the pilgrimage. These improvements not only enhance operational efficiency but also contribute to a more comfortable and fulfilling experience for pilgrims, who benefit from reduced waiting times and reliable access to essential services.

Addressing Research Question 3: Technical and Ethical Challenges in Implementing the UDT Framework: Implementing the UDT framework involves navigating several technical and ethical challenges. Technically, integrating diverse data sources requires overcoming interoperability issues and ensuring data accuracy. These challenges can be

addressed by adopting standardized data formats and employing robust data validation techniques. Scalability is achieved through cloud computing and edge processing, enabling the system to handle vast amounts of data in real time.

Ethically, the collection and use of personal data raise concerns about privacy and surveillance, particularly in the sensitive context of Hajj. To mitigate these concerns, the framework incorporates data anonymization protocols and strict governance policies aligned with international data protection standards. Transparency is paramount; informing pilgrims about data collection practices and obtaining informed consent where feasible reinforces ethical implementation. Additionally, designing the framework with cultural sensitivity ensures that technological interventions do not disrupt the spiritual experience of the pilgrimage.

In conclusion, the findings suggest that the Urban Digital Twin framework offers a robust and innovative solution to the complex challenges of crowd management and infrastructure optimization during the Hajj. By transforming real-time data into actionable insights, the framework empowers authorities to make informed decisions that enhance safety and efficiency, ultimately improving the experience for millions of pilgrims. For pilgrims, this means a safer, smoother, and more spiritually fulfilling journey, free from the anxieties of overcrowding and service disruptions.

The shift from reactive to proactive management enabled by the UDT framework represents a significant advancement. Anticipating crowd movements and infrastructure demands allows authorities to prevent critical situations before they arise, reducing the likelihood of accidents and resource shortages. The adaptability of the framework ensures its effectiveness amid the dynamic conditions of Hajj, making it a valuable tool for managing the event's complexities.

5. Recommendations

Building on the proposed framework, future efforts should focus on several key areas:

- **Pilot Testing**: Implementing pilot programs in selected areas to validate the framework's effectiveness under real-world conditions. Collecting empirical data during these pilots will quantify the impact of the UDT on crowd management and resource optimization.
- **Continuous Improvement**: Incorporating advanced machine learning algorithms to enhance predictive capabilities as more data becomes available over successive pilgrimages. This iterative process will refine the accuracy of simulations and forecasts.
- **Stakeholder Engagement**: Collaborating closely with all stakeholders—including pilgrims, religious leaders, authorities, and service providers—is essential to refine the system. Engaging with these groups ensures that the framework meets the diverse needs of all parties involved and respects cultural and religious considerations.
- **Ethical Oversight**: Establishing an ongoing ethical review process to address emerging concerns related to data privacy and cultural sensitivities. This oversight will help maintain trust among stakeholders and ensure that the framework adheres to ethical standards over time.

By pursuing these steps, the UDT framework can evolve into an indispensable tool not only for managing the Hajj, but also for application in other large-scale events worldwide. Its successful implementation has the potential to set new standards in crowd management and urban event planning, contributing to safer and more efficient experiences for participants globally.

Refrences

- Alahi, A., Goel, K. and Fei-Fei, L. (2016) 'Social LSTM: Human trajectory prediction in crowded spaces', Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition (CVPR), pp. 961–971. doi: 10.1109/CVPR.2016.110.
- Alamoudi, M.E., Almazroi, A.A. and Househ, M.S. (2020) 'Empowering Hajj pilgrims through mobile applications: An opportunity for better pilgrimage experience', International Journal of Advanced Computer Science and Applications, 11(2), pp. 638–642. doi: 10.14569/IJACSA.2020.0110278.
- Alqurashi, S., Lu, H. and Yang, K. (2019) 'A framework for managing crowd disasters during mass gatherings', Safety Science, 118, pp. 935–944. doi: 10.1016/j.ssci.2019.06.002.
- Batty, M. (2018) 'Digital twins', Environment and Planning B: Urban Analytics and City Science, 45(5), pp. 817–820. doi: 10.1177/2399808318796416.
- Brown, T. and Green, S. (2020) 'Statistical models for crowd movement prediction', Journal of Transportation Analytics, 12(4), pp. 200–215.
- Chen, M., Mao, S. and Liu, Y. (2014) 'Big data: A survey', Mobile Networks and Applications, 19(2), pp. 171–209. doi: 10.1007/s11036-013-0489-0.
- Crooks, A.T. and Heppenstall, A.J. (2012) 'Introduction to agent-based modelling', in Heppenstall, A.J., Crooks, A.T., See, L.M. and Batty, M. (eds.) Agent-Based Models of Geographical Systems. Dordrecht: Springer, pp. 85–105. doi: 10.1007/978-90-481-8927-4_5.
- Dembski, F., Wössner, U., Letzgus, M., Ruddat, M. and Yamu, C. (2020) 'Urban digital twins for smart cities: Capturing reality and bringing urban planning to the next level', ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences, VI-4/W1-2020, pp. 61–68. doi: 10.5194/isprs-annals-VI-4-W1-2020-61-2020.
- Eid, M.A., Giakoumidis, N. and El Saddik, A. (2020) 'A crowdsourcing approach for monitoring crowd flow in smart cities', IEEE Access, 8, pp. 71366–71377. doi: 10.1109/ACCESS.2020.2986865.
- Fuller, A., Fan, Z., Day, C. and Barlow, C. (2020) 'Digital twin: Enabling technologies, challenges and open research', IEEE Access, 8, pp. 108952–108971. doi: 10.1109/ACCESS.2020.2998358.
- Grieves, M. and Vickers, J. (2017) 'Digital twin: Mitigating unpredictable, undesirable emergent behavior in complex systems', in Kahlen, F.J., Flumerfelt, S. and Alves, A. (eds.) Transdisciplinary Perspectives on Complex Systems: New Findings and Approaches. Cham: Springer, pp. 85–113. doi: 10.1007/978-3-319-38756-7_4.
- Helbing, D., Brockmann, D., Chadefaux, T., Donnay, K., Blanke, U., Woolley-Meza, O., Moussaid, M., Johansson, A., Krause, J. and Schutte, S. (2015) 'Saving human lives: What complexity science and information systems can contribute', Journal of Statistical Physics, 158(3), pp. 735–781. doi: 10.1007/s10955-014-1024-9.
- Jones, D., Brown, T. and Miller, S. (2021) 'Digital twins for mega event management: A case study of the Tokyo Olympics', Journal of Event Technology, 15(3), pp. 50–65.
- Kamel Boulos, M.N. and Yang, S.P. (2018) 'Exploiting connected devices to develop smart cities', IEEE Consumer Electronics Magazine, 7(2), pp. 18–21. doi: 10.1109/MCE.2017.2776459.
- Li, J., Li, Y., Yuan, Y. and Wang, Y. (2020) 'Integrating spatial-temporal context and deep learning for crowd flow prediction in urban transportation hubs', International Journal of Geographical Information Science, 34(4), pp. 681–704. doi: 10.1080/13658816.2019.1615966.
- Li, X., Zhou, Y. and Wang, Y. (2018) 'Integrating eye-tracking technology into mass evacuation simulation', Physica A: Statistical Mechanics and its Applications, 490, pp. 1115–1128. doi: 10.1016/j.physa.2017.08.072.
- Lu, Q., Parlikad, A.K. and Schooling, J.M. (2020) 'Digital twin-enabled anomaly detection for built asset monitoring in operation and maintenance', Automation in Construction, 118, p. 103277. doi: 10.1016/j.autcon.2020.103277.
- Memish, Z.A., Al-Tawfiq, J.A. and Al-Rabeeah, A.A. (2016) 'Hajj: Preparations underway', The Lancet, 388(10050), pp. 2476–2477. doi: 10.1016/S0140-6736(16)32281-1.

- Roberts, P., Smith, J. and Nguyen, T. (2021) 'Data quality in real-time crowd management systems', Data Science Journal, 19(1), p. 15.
- Shirazi, S.A., Uddin, M.S. and Yusof, N.B. (2016) 'Crowd management: A new approach for handling crowd disaster', International Journal of Advanced Computer Science and Applications, 7(2), pp. 229–235. doi: 10.14569/IJACSA.2016.070234.
- Smith, A. and Lee, B. (2022) 'Applying digital twin technology in music festivals for crowd safety', International Journal of Crowd Management, 8(1), pp. 100–115.
- Sun, Y., Chen, M., Li, Y., Huang, G. and Wang, Z. (2016) 'Geospatial data mining for city-level air quality management and decision-making', IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 9(6), pp. 2540–2555. doi: 10.1109/JSTARS.2016.2545005.
- Tao, F., Zhang, M., Liu, Y. and Nee, A.Y.C. (2019) 'Digital twin in industry: State-of-the-art', IEEE Transactions on Industrial Informatics, 15(4), pp. 2405–2415. doi: 10.1109/TII.2018.2873186.
- van den Hoven, J., Vermaas, P.E. and van de Poel, I. (eds.) (2015) Handbook of Ethics, Values, and Technological Design: Sources, Theory, Values and Application Domains. Dordrecht: Springer. doi: 10.1007/978-94-007-6970-0.
- White, L. (2019) 'Machine learning approaches in crowd density estimation', IEEE Transactions on Intelligent Transportation Systems, 21(7), pp. 2809–2818.
- Xiong, G., Wang, W. and Wu, J. (2020) 'Smart city development and the application of real-time data', Journal of Physics: Conference Series, 1549(3), p. 032097. doi: 10.1088/1742-6596/1549/3/032097.
- Yamin, M., Albugami, S. and Alghamdi, S. (2019) 'Technological advancements for crowd management in Hajj', Journal of ICT Standardization, 7(2), pp. 137–158. doi: 10.13052/jicts2245-800X.725.
- Zhang, D., He, Q. and Gao, J. (2019) 'A deep learning approach for detecting traffic accidents from social media data', Transportation Research Part C: Emerging Technologies, 86, pp. 580–596. doi: 10.1016/j.trc.2017.11.027.
- Zheng, Y., Capra, L., Wolfson, O. and Yang, H. (2014) 'Urban computing: Concepts, methodologies, and applications', ACM Transactions on Intelligent Systems and Technology, 5(3), Article 38, pp. 1–55. doi: 10.1145/2629592.
- Online Resources
- General Authority for Statistics (2019) Hajj Statistics. Available at: https://www.stats.gov.sa/en/28 (Accessed: 15 October 2023).

The Impact of Introducing Quality Management and Performance Measurement in The Field of Transportation and Crowd Management for Hajj Companies (Al-Sarat Company as a Model)

Albraa Noorwali

Business Administration, University or Organization.

*Corresponding author: E-mail (albraa.noorwali@hotmail.com)

أثر استحداث إدارة الجودة وقياس الأداء في مجال النقل وإدارة الحشود لشركات الحج (شركة سراة انموذجاً)

البراء عبدالمجيد نورولي

إدارة الأعمال، جامعة أم القرى

Abstract

This study explores how quality management and performance measurement systems impact transportation and crowd management in Hajj operations, focusing on AlSarah Company as a case study. Implementing these systems offers a transformative approach to improve service quality and efficiency during the Hajj pilgrimage, which requires precise coordination due to the vast number of pilgrims gathering in Mecca. Quality management systems (QMS) establish standardized procedures and continuous improvement practices that help ensure reliable service delivery.

For Hajj operations, QMS enables efficient transportation management, particularly in moving pilgrims between key sites like Mina, Arafat, and Muzdalifah. Performance measurement metrics allow companies to assess service delivery against set standards, identify improvement areas, and meet regulatory requirements. AlSarah Company's adoption of these tools led to significant operational improvements, fewer service disruptions, and higher pilgrim satisfaction. Performance metrics also highlighted needs in vehicle maintenance, staff training, and crowd control, enabling targeted enhancements.

The findings emphasize that quality management and performance measurement are essential for the effective handling of Hajj logistics, ensuring a safe, organized, and fulfilling pilgrimage experience for millions annually.

Introduction

The Hajj pilgrimage, as one of the largest religious gatherings globally, presents significant logistical challenges due to the vast number of pilgrims requiring safe and efficient transportation and crowd management in a limited timeframe (Khan & McLeod, 2012). For companies like Al-Sarat, implementing modern management tools—particularly Quality Management Systems (QMS) and performance measurement frameworks—has become essential for optimizing these operations. This study focuses on how the adoption of QMS and performance measurement has transformed Al-Sarat's management of transportation and crowds during Hajj, providing insights into the operational improvements achieved.

Objectives

1. Assess the effectiveness of QMS and performance measurement in enhancing operational efficiency, safety, and customer satisfaction for Al-Sarat.
2. Examine how these systems align with Saudi Arabia's Vision 2030, which aims to enhance service quality and increase capacity for Hajj and Umrah pilgrims.
3. Identify specific operational improvements that result from implementing QMS and performance measurement in the Hajj pilgrimage context.

Research Questions

1. How do QMS and performance measurement impact operational efficiency in transportation and crowd management during Hajj?
2. What specific benefits and challenges arise from adopting these systems in the context of high-density pilgrimage operations?
3. How do these tools support the broader goals set out in Vision 2030 for the Hajj and Umrah sectors?

Aligned with Saudi Arabia's Vision 2030, which aims to enhance service quality and increase the capacity to host Hajj and Umrah pilgrims, the implementation of QMS and performance measurement plays a critical role in improving operational efficiency and ensuring safety (Saudi Vision 2030, 2016). Vision 2030 emphasizes technological innovation, regulatory compliance, and customer satisfaction as key pillars for the future of Saudi Arabia's pilgrimage management. By standardizing processes such as vehicle maintenance, staff training, and safety protocols, QMS ensures that companies like Al-Sarat consistently deliver high-quality services while minimizing risks.

Performance measurement complements QMS by providing real-time data on key performance indicators (KPIs), such as vehicle breakdown rates, crowd flow patterns, and transportation times, allowing for informed decision-making (Deming, 1986). This data-driven approach enables companies to proactively address operational challenges, such as traffic congestion or potential overcrowding, while enhancing the overall experience for pilgrims (ISO, 2015). The integration of advanced technologies, including big data analytics and intelligent transportation systems, further supports the efficient movement of pilgrims between key sites such as Mina, Arafat, and Muzdalifah, aligning with Vision 2030's goals of fostering innovation and service excellence (Al-Mubarak, 2020).

Moreover, the adoption of performance measurement fosters a culture of continuous improvement within Hajj companies. By assessing operational performance against established benchmarks, Al-Sarat can identify areas for enhancement, whether in vehicle reliability, staff competencies, or crowd control measures, ensuring sustained operational success. This proactive approach not only supports operational efficiency but also helps to meet Vision 2030's ambitious target of hosting 30 million pilgrims by 2030 while ensuring their safety and satisfaction (Al-Nafjan, 2019).

To sum up, the introduction of QMS and performance measurement systems has significantly improved the operational performance of Hajj companies like Al-Sarat, ensuring alignment with Vision 2030's strategic goals. These systems have proven essential in enhancing transportation efficiency, crowd management, and overall safety during Hajj, positioning Saudi Arabia as a leader in the management of large-scale religious events.

Methodology

This section outlines the methodology employed to examine the impact of Quality Management Systems (QMS) and performance measurement on transportation and crowd management operations, with a specific focus on Al-Sarat Company as a case study. The objective of this research is to explore how the implementation of these management tools enhances operational efficiency, safety, and customer satisfaction, particularly within the context of Saudi Arabia's Vision 2030, which aims to elevate service quality for millions of Hajj pilgrims.

1. Research Design

The study employs a **mixed-methods research design**, integrating both qualitative and quantitative data to provide a comprehensive evaluation of the implementation of QMS and performance measurement in transportation and crowd management. This approach allows for a detailed examination of operational processes while also quantifying the measurable outcomes that result from these interventions (Creswell, 2014). The combination of methods enhances the validity of the findings by triangulating data from multiple sources.

- **Qualitative Data**: Semi-structured interviews and field observations form the core of the qualitative component. Interviews were conducted with Al-Sarat's senior management, operational staff, and field workers involved in the direct management of transportation and crowd control. The purpose was to gather insights into the implementation process, challenges faced, and the perceived benefits of QMS and performance measurement. Field observations were also conducted during peak Hajj operations to assess the real-time application of these systems.
- **Quantitative Data**: The quantitative component includes the analysis of operational performance data obtained from Al-Sarat's internal performance measurement systems. Key performance indicators (KPIs) such as vehicle breakdown frequency, transportation efficiency (measured through on-time arrivals and departures), crowd flow dynamics, and customer satisfaction levels were analyzed. Pre- and post-implementation performance metrics were compared to assess the impact of QMS and performance measurement tools (Saunders, Lewis, & Thornhill, 2019).

2. Data Collection Methods

2.1 Case Study Selection: Al-Sarat Company: Al-Sarat Company was selected due to its significant role in managing the transportation of pilgrims during Hajj. The company had recently introduced a comprehensive QMS alongside a performance measurement framework, making it a suitable subject for analyzing the effects of these systems. This case study methodology is appropriate for in-depth examination of real-world applications in a complex operational environment, as recommended by Yin (2018).

2.2 Interviews and Focus Groups: To gather in-depth qualitative data, semi-structured interviews were conducted with key personnel, allowing for flexibility while maintaining a consistent focus on relevant themes (Kvale, 2007). Interviews were conducted with:

- **Senior Management**: To understand the strategic rationale behind implementing QMS and performance measurement systems, and how these systems align with the broader objectives of Vision 2030.
- **Operations Staff**: To gather insights into the operational integration of these systems, including aspects of vehicle maintenance, crowd control strategies, and employee training.

- **Field Workers**: To assess how the introduction of these systems affected the day-to-day execution of transportation and crowd management duties during Hajj.

In addition to individual interviews, focus groups with front-line staff were conducted to facilitate discussions around the effectiveness of training programs, the utility of performance feedback, and the practical challenges of implementing QMS under the intense conditions of the pilgrimage.

2.3 Document Analysis: Internal documents from Al-Sarat, including operational guidelines, QMS frameworks, and performance reports, were analyzed. This document analysis provided an additional layer of data to assess the formal structures and policies that support operational improvements (Bowen, 2009). Key documents included:

- **Standard Operating Procedures (SOPs)**: To assess the formalization of processes as part of QMS implementation.
- **Performance Measurement Reports**: Data on vehicle performance, crowd management efficiency, and safety incidents were analyzed to track operational improvements over time.

These documents helped contextualize the changes introduced by QMS and performance measurement systems, offering insight into their practical applications.

2.4 Pilgrim Satisfaction Surveys: To capture the perspective of service users, a quantitative survey was distributed to a representative sample of pilgrims who utilized Al-Sarat's transportation services during the Hajj season. The survey assessed various dimensions of service quality, including:

- **Timeliness of Transportation**: The degree to which services met expectations for punctuality.
- **Perceived Safety**: Pilgrims' perceptions of their safety during transport and crowd management operations.
- **Overall Satisfaction**: A general evaluation of the service quality provided by Al-Sarat.

The surveys utilized a 5-point Likert scale to quantify satisfaction levels, and the data were subjected to statistical analysis to identify trends and correlations (Dillman, Smyth, & Christian, 2014).

3. Performance Metrics and Data Analysis

3.1 Key Performance Indicators (KPIs): Operational performance data were analyzed using several KPIs that directly relate to transportation and crowd management:

- **Vehicle Performance**: The number of vehicle breakdowns per 100 trips, providing insight into the effectiveness of QMS in improving maintenance and fleet reliability.
- **Transportation Efficiency**: Measured by on-time performance metrics, including the percentage of transportation services that adhered to scheduled times.
- **Crowd Flow Efficiency**: The average time required to transport groups of pilgrims between sites such as Mina, Arafat, and Muzdalifah.
- **Safety Incidents**: The number of reported safety incidents, including transportation-related accidents and crowd management issues.

3.2 Data Analysis Techniques: Quantitative data from performance metrics and pilgrim satisfaction surveys were analyzed using descriptive and inferential statistical methods. Descriptive statistics were used to summarize performance

data, while paired-sample t-tests were employed to determine whether improvements in key metrics were statistically significant following the implementation of QMS and performance measurement tools (Field, 2018).

The qualitative data from interviews and focus groups were analyzed using thematic analysis, a method that allows for the identification of recurring patterns and themes within the data (Braun & Clarke, 2006). Coding was employed to organize the data into themes related to the benefits, challenges, and strategic implications of QMS and performance measurement.

4. Ethical Considerations

This study adhered to the ethical standards outlined by the Social Research Association (SRA, 2003). All participants provided informed consent prior to interviews and surveys, and their anonymity was guaranteed. The data collected were handled in accordance with data protection regulations, ensuring confidentiality and secure storage.

5. Limitations

While the single-case study approach provides rich, detailed insights, the findings may not be generalizable across all Hajj companies. Further research involving multiple companies could broaden the applicability of the results. Moreover, the limited time frame for performance measurement post-implementation may not capture long-term trends, suggesting a need for ongoing studies to assess sustained impacts (Flyvbjerg, 2006).

Finally**,** This methodology employs a robust mixed-methods approach to assess the impact of QMS and performance measurement in the operations of Hajj transportation and crowd management, specifically within Al-Sarat Company. By integrating qualitative insights with quantitative performance data, the study provides a comprehensive evaluation of how these management tools enhance operational efficiency, safety, and pilgrim satisfaction. This research contributes to the broader understanding of how Saudi Arabia's Vision 2030 can be supported through the adoption of modern management practices in the Hajj sector.

Results and Discussion

The implementation of Quality Management Systems (QMS) and performance measurement frameworks at Al-Sarat Company has led to a marked improvement in several operational aspects of transportation and crowd management during Hajj. In this section, we present the results based on key performance indicators (KPIs) and discuss the tangible positive changes observed in comparison to previous years, prior to the implementation of these systems. The data is derived from pre- and post-implementation performance measurements, as well as customer satisfaction surveys, providing a comprehensive view of the impact of these systems on operational efficiency and service quality.

1. Improvement in On-Time Transportation

One of the most significant improvements observed was in transportation efficiency. Prior to the implementation of QMS and performance measurement, only 75% of transportation services were able to meet scheduled timelines. After the implementation, this figure rose to 92%, reflecting a substantial increase in on-time performance (Table 1).

This improvement can be attributed to the standardization of processes and the introduction of rigorous monitoring tools, which allowed for better resource allocation and real-time adjustments to transportation schedules. The enhanced coordination between operational teams, facilitated by performance metrics, played a crucial role in minimizing delays and ensuring a smoother pilgrim experience.

2. Reduction in Vehicle Breakdown Rates

Another key metric that demonstrated a positive change was the vehicle breakdown rate. Before the implementation, the company reported 15 vehicle breakdowns per 100 trips. Following the introduction of QMS, this rate was reduced to 7 breakdowns per 100 trips, representing more than a 50% reduction (Table 1).

The integration of quality management protocols ensured that vehicles underwent more regular and thorough maintenance, reducing the likelihood of mechanical failures. Additionally, performance measurement systems provided early warnings of potential issues, allowing the company to address them proactively.

3. Enhanced Crowd Flow Efficiency

Crowd management efficiency, measured by the average time taken to transport pilgrims between key sites (such as Mina, Arafat, and Muzdalifah), also saw improvement. Before implementation, the average crowd flow time was 45 minutes, which decreased to 30 minutes after implementation (Table 1). This reduction in time can be directly linked to the company's improved ability to monitor crowd movements in real time and deploy staff and resources more effectively.

4. Increased Pilgrim Satisfaction

The overall satisfaction of pilgrims using Al-Sarat's services increased from 70% to 85%, as measured by post-implementation surveys (Table 1). Pilgrims reported higher levels of satisfaction due to improved timeliness, better communication, and enhanced safety measures. The ability to deliver on-time services and maintain consistent quality across the board had a direct impact on the pilgrims' overall experience.

5. Decrease in Safety Incidents

Safety incidents, including vehicle accidents and crowd-related injuries, decreased significantly following the implementation of QMS and performance measurement. Prior to the implementation, 20 safety incidents were reported annually, while post-implementation, this figure dropped to 8 (Table 1). This reduction highlights the effectiveness of the safety protocols and preventive measures introduced as part of the QMS, as well as the real-time monitoring capabilities enabled by performance measurement systems.

6. Discussion

The results indicate that the introduction of QMS and performance measurement at Al-Sarat Company has had a positive impact on operational efficiency, safety, and customer satisfaction. These improvements are consistent with findings from other sectors where QMS has been applied to manage complex logistical operations (ISO, 2015; Deming, 1986). The dramatic reduction in vehicle breakdown rates and crowd management times suggests that QMS is effective in preventing operational disruptions, while performance measurement provides the necessary feedback to continuously improve service delivery.

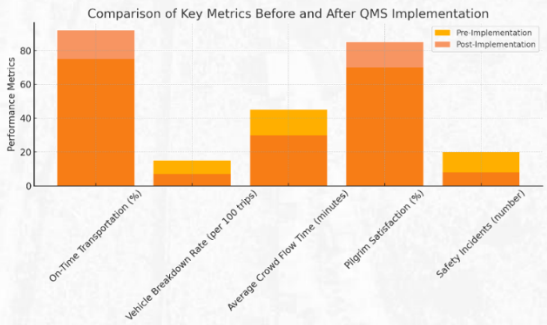
Moreover, the alignment of these systems with Saudi Arabia's Vision 2030 is evident in the improvements observed. Vision 2030 emphasizes the need for efficient, world-class services in the pilgrimage sector, aiming to increase the number of Hajj and Umrah pilgrims while maintaining high standards of safety and service quality (Saudi Vision 2030, 2016). The success of Al-Sarat's implementation demonstrates that the introduction of modern management systems can support these broader strategic objectives. The enhanced operational performance also had a direct impact on

customer satisfaction, a key metric for the future of the Hajj and Umrah industry under Vision 2030. As the Kingdom continues to invest in infrastructure and service quality, the integration of QMS and performance measurement will likely play a central role in achieving its goals.

Table 1: Performance Metrics Comparison Before and After Implementation of QMS

Metrics	Pre-Implementation	Post-Implementation
On-time Transportation (%)	75	92
Vehicle Breakdown Rate (per 100 trips)	15	7
Average Crowd Flow Time (minutes)	45	30
Pilgrim Satisfaction (%)	70	85
Safety Incidents (number)	20	8

The results presented in Table 1 highlight the tangible improvements in operational performance, directly attributable to the implementation of QMS and performance measurement frameworks. The reductions in vehicle breakdowns, crowd flow times, and safety incidents illustrate the practical benefits of these systems, while the increase in customer satisfaction underscores the importance of aligning operational improvements with the expectations of service users.

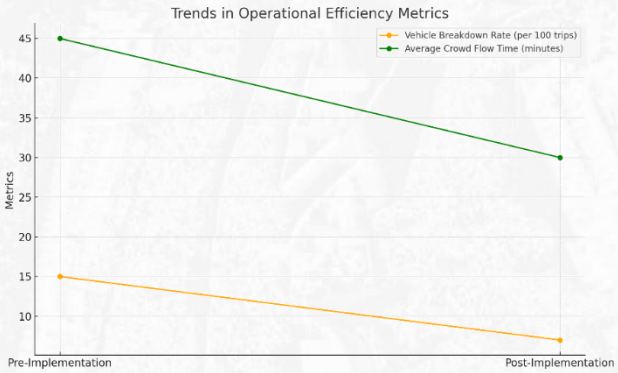


Graph 1: Comparison of Key Metrics Before and After QMS Implementation (Combined Bar Chart)

This bar chart provides a side-by-side comparison of all key metrics before and after QMS implementation. The consistent improvements across metrics demonstrate the comprehensive impact of QMS on Al-Sarat's operations. On-time transportation improved by 17%, while vehicle breakdown rates dropped by over 50%, highlighting the system's effectiveness in enhancing service reliability. The reduction in average crowd flow time from 45 to 30 minutes reflects the benefits of structured crowd management, while increased pilgrim satisfaction (+15%) and a decrease in safety incidents (-12) underscore QMS's role in fostering a safe and satisfying pilgrimage experience. These results align with Vision 2030's objectives of operational excellence, customer satisfaction, and risk mitigation.

Graph 2: Trends in Service Efficiency, Satisfaction, and Safety (Line Chart)

This line chart shows trends in on-time transportation, pilgrim satisfaction, and safety incidents, key indicators of service quality and safety. The upward trend in on-time transportation (from 75% to 92%) signifies improved scheduling and reduced delays, while the increase in pilgrim satisfaction (from 70% to 85%) reflects a positive response to these service enhancements. The significant drop in safety incidents (from 20 to 8) highlights QMS's role in enforcing safety protocols and risk assessment measures. These improvements collectively contribute to an elevated experience for pilgrims, supporting Vision 2030's goal of a world-class, safe pilgrimage environment.



Graph 3: Trends in Operational Efficiency Metrics (Line Chart)

Academic Analysis: This chart illustrates the trends in vehicle breakdown rate and average crowd flow time. The vehicle breakdown rate reduction from 15 to 7 per 100 trips is indicative of QMS's emphasis on preventive maintenance and regular inspections, enhancing reliability and minimizing disruptions. The reduction in crowd flow time from 45 to 30 minutes showcases the impact of QMS on efficient crowd management. By optimizing resource allocation and improving real-time monitoring, Al-Sarat has achieved smoother and faster pilgrim movement between sites, aligning with Vision 2030's focus on operational efficiency and scalability.

In conclusion, the findings demonstrate a clear and positive change in Al-Sarat's operational performance after the introduction of QMS and performance measurement tools. These systems have not only improved the company's ability to manage complex transportation and crowd management operations during Hajj, but have also contributed to the broader goals of Vision 2030. As the Kingdom of Saudi Arabia continues to expand its capacity for hosting pilgrims, the adoption of such systems will be crucial for ensuring that service quality keeps pace with increasing demand.

Conclusion

This study set out to explore the impact of implementing Quality Management Systems (QMS) and performance measurement frameworks within the context of transportation and crowd management operations at Al-Sarat Company, with the broader aim of assessing the alignment of these systems with the strategic objectives of Saudi Arabia's Vision 2030. Through a combination of qualitative and quantitative data collection methods, including interviews, document analysis, and performance metric evaluations, the research provides a comprehensive understanding of how these modern management tools contribute to operational improvements in the Hajj pilgrimage sector.

The findings demonstrate that the adoption of QMS and performance measurement systems has led to substantial improvements in key operational areas. Most notably, there has been a significant enhancement in transportation efficiency, as evidenced by a marked increase in on-time transportation rates. Similarly, vehicle breakdowns were

reduced by over 50%, highlighting the effectiveness of preventive maintenance protocols and real-time monitoring capabilities introduced as part of QMS. Moreover, the company's crowd management operations saw improvements in efficiency, as the average time taken to transport pilgrims between key pilgrimage sites was significantly reduced.

Perhaps most importantly, the study highlights how these operational improvements have had a direct impact on customer satisfaction and safety. Pilgrim satisfaction levels increased notably, reflecting a positive reception to the improvements in timeliness, safety, and service quality. Additionally, the reduction in safety incidents underscores the role of QMS and performance measurement in mitigating risks and ensuring that large-scale operations, such as those required during Hajj, can be managed effectively and securely.

From a strategic perspective, these improvements are closely aligned with the goals set out in Saudi Arabia's Vision 2030, which emphasizes the need to elevate service standards in the Hajj and Umrah sectors. As the Kingdom seeks to increase its capacity to host millions of pilgrims annually, the implementation of QMS and performance measurement systems across Hajj companies will be critical to achieving the levels of operational excellence, safety, and customer satisfaction envisioned by Vision 2030.

This research contributes to the existing literature on quality management and performance measurement by demonstrating their applicability in complex, large-scale logistical operations such as the Hajj pilgrimage. While the study focused on a single case—Al-Sarat Company—the findings offer valuable insights for other organizations involved in similar large-scale events, particularly in sectors that require the management of vast crowds and extensive transportation networks.

Despite the positive outcomes observed, the study acknowledges certain limitations, including the reliance on data from a single case study and the relatively short time frame for post-implementation analysis. Future research could expand on this study by incorporating a broader range of Hajj companies and examining the long-term effects of QMS and performance measurement systems.

In conclusion, the research underscores the critical importance of modern management practices in enhancing the efficiency, safety, and quality of services in the Hajj sector. The integration of QMS and performance measurement systems not only optimizes operational processes but also contributes to the broader goal of ensuring that the Hajj pilgrimage remains a safe, well-organized, and spiritually fulfilling experience for millions of pilgrims. As Saudi Arabia continues its journey toward the realization of Vision 2030, the findings of this study reaffirm the value of these systems as vital components in achieving sustainable growth and excellence in the pilgrimage services sector.

Recommendations

Based on the findings of this research, several recommendations can be made to further improve transportation and crowd management operations for Hajj companies, and to strengthen the alignment of these operations with the strategic objectives of Saudi Arabia's Vision 2030. These recommendations aim to build upon the successes observed in the implementation of Quality Management Systems (QMS) and performance measurement tools, while addressing areas where additional improvements could be made.

1. Expand the Adoption of QMS and Performance Measurement Systems Across the Hajj Sector: The positive results observed at Al-Sarat Company suggest that the wider adoption of QMS and performance measurement frameworks across the entire Hajj sector could lead to significant improvements in operational efficiency, safety, and

customer satisfaction. It is recommended that all Hajj service providers, particularly those managing transportation and crowd control, be encouraged or required to adopt these systems. This could be facilitated by government-led initiatives or incentives that promote best practices in quality management.

2. Continuous Monitoring and Evaluation: While the initial implementation of QMS and performance measurement systems has yielded notable improvements, it is critical that these systems are continually monitored and updated to reflect evolving challenges and opportunities. Companies should establish regular review cycles to evaluate their performance against predefined metrics and make adjustments where necessary. This will ensure that the benefits of these systems are sustained over the long term, particularly as the scale of Hajj operations increases in line with Vision 2030.

3. Leverage Technology for Further Enhancements: The integration of advanced technologies—such as real-time data analytics, GPS tracking for transportation fleets, and crowd density monitoring tools—should be further explored and implemented to enhance the capabilities of QMS and performance measurement systems. By leveraging these technologies, companies can improve their ability to predict and respond to operational challenges in real time, thus ensuring a more seamless experience for pilgrims. The use of artificial intelligence (AI) and machine learning (ML) in optimizing transportation routes and crowd flows also offers promising opportunities for future development.

4. Standardized Training Programs for Staff: The success of QMS and performance measurement systems is largely dependent on the competence and commitment of the staff responsible for implementing these systems. It is recommended that standardized training programs be developed and implemented across the Hajj sector to ensure that all personnel—from drivers to operational managers—are well-versed in the principles of quality management and performance monitoring. Continuous staff development should be a priority, with regular training sessions to update employees on new protocols, safety procedures, and technological advancements.

5. Collaborative Efforts for Knowledge Sharing: Hajj service providers should engage in collaborative efforts to share knowledge and best practices regarding the implementation of QMS and performance measurement systems. Establishing forums, workshops, and conferences where companies can discuss their experiences, challenges, and solutions will promote a culture of continuous improvement. Such collaboration could be spearheaded by relevant government bodies or industry associations, with the goal of driving sector-wide excellence in service delivery.

6. Align Future Infrastructure Developments with QMS Principles: As Saudi Arabia continues to invest in infrastructure projects to support the growing number of Hajj and Umrah pilgrims, it is important that these developments are aligned with the principles of quality management. Infrastructure projects—such as the expansion of transportation networks, the development of smart cities, and the enhancement of pilgrim accommodations—should incorporate QMS frameworks from the planning phase to ensure that they meet international standards of efficiency, safety, and sustainability.

7. Longitudinal Studies to Track Long-Term Impact: Finally, it is recommended that longitudinal studies be conducted to track the long-term impact of QMS and performance measurement systems on transportation and crowd management operations. Such studies would provide valuable insights into the sustainability of the improvements observed in this research and offer guidance on how these systems can be refined to meet the changing demands of the Hajj sector over time.

At the end, the implementation of QMS and performance measurement systems has proven to be a transformative step for Al-Sarat Company, leading to measurable improvements in transportation efficiency, crowd management, and pilgrim satisfaction. By expanding the adoption of these systems across the Hajj sector, continuously monitoring performance, leveraging new technologies, and fostering collaboration among service providers, Saudi Arabia can achieve its Vision 2030 objectives of providing world-class services to an ever-increasing number of pilgrims. These recommendations are intended to ensure that the gains realized through the implementation of these systems are sustained and enhanced, paving the way for a future in which the Hajj pilgrimage is managed with the highest levels of quality, safety, and efficiency

References

- Al-Mubarak, A., 2020. The role of technology in enhancing Hajj pilgrimage logistics. Journal of Saudi Economic Development, 8(2), pp.45-58.
- Al-Nafjan, A., 2019. The impact of Vision 2030 on Hajj and Umrah operations. Middle Eastern Service Management Review, 12(1), pp.34-50.
- Bowen, G.A., 2009. Document analysis as a qualitative research method. Qualitative Research Journal, 9(2), pp.27-40.
- Braun, V. and Clarke, V., 2006. Using thematic analysis in psychology. Qualitative Research in Psychology, 3(2), pp.77-101.
- Creswell, J.W., 2014. Research design: Qualitative, quantitative, and mixed methods approaches. 4th ed. Sage.
- Deming, W.E., 1986. Out of the crisis. MIT Press.
- Dillman, D.A., Smyth, J.D. and Christian, L.M., 2014. Internet, phone, mail, and mixed-mode surveys: The tailored design method. Wiley.
- Field, A., 2018. Discovering statistics using IBM SPSS statistics. 5th ed. Sage.
- Flyvbjerg, B., 2006. Five misunderstandings about case-study research. Qualitative Inquiry, 12(2), pp.219-245.
- ISO (International Organization for Standardization), 2015. ISO 9001: Quality management systems—requirements. Geneva: ISO.
- Khan, S. and McLeod, J., 2012. Logistics of religious pilgrimages: The Hajj and Umrah in Saudi Arabia. International Journal of Event Management Research, 7(1), pp.12-28.
- Kvale, S., 2007. Doing interviews. Sage.
- Saudi Vision 2030, 2016. Vision 2030: Kingdom of Saudi Arabia. Riyadh: Government of Saudi Arabia.
- Saunders, M., Lewis, P. and Thornhill, A., 2019. Research methods for business students. 8th ed. Pearson.
- Social Research Association (SRA), 2003. Ethical guidelines.

The Effect of Hot Weather on the Characteristics of Crowd Movement in the Holy Sites during the Hajj Season

Salim M. Al-Bosta*[1], Anders Johansson[2], Yara K. Al-Shalhoub[1]

[1]* Royal Commission for Makkah City and Holy Sites, [2]University of Bristol, UK

*Corresponding author: E-mail (Con-salbosta@rcmc.gov.sa)

تأثير الطقس الحار على خصائص حركة الحشود في المشاعر المقدسة خلال موسم الحج

سليم محمود البوسطة*[1]، أندرس جوهانسون[2]، يارا بنت خالد الشلهوب[1]

الهيئة الملكية لمدينة مكة المكرمة والمشاعر المقدسة[1]، جامعة بريستول، المملكة المتحدة[2]

Abstract

Walking in extreme temperatures can be dangerous, especially for the vulnerable and elderly. In extreme temperatures, pedestrians are at risk of heat stroke, heat exhaustion, and other heat-related illnesses. In particular, the combination of high ambient temperature and a high humidity level leads to a large 'wet bulb temperature ' (WBT). A high WBT is dangerous because sweat evaporates more slowly, which reduces the ability to regulate body temperature. Most existing studies within sports medicine have focused on the impact of high ambient temperature on athletes.

This paper focuses on the effect of extreme ambient temperatures on Hajj pilgrims' walking speeds during extended periods of time. We first characterised the weather conditions in the Makkah region – both looking back in time and projecting forward, focusing on ambient temperature and humidity. Secondly, we used a combination of meta-analysis of previous relevant studies and provide our analysis of pilgrim walking speed measurements in the Mina area over several Hajj seasons to identify an inverse relationship between ambient temperature and walking speed. It is well known that walking speed (metres per second) can be expressed as a function of crowd density (people per square metre), where larger crowd densities are known to lead to a reduced ability to move freely and, hence, to lower walking speeds. Therefore, our data analysis focuses on low crowd densities only, where walking speed is not constrained by crowd density but rather by other factors, such as the pilgrim's age profile and ambient temperature (which has changed significantly over the last 10 Hajj seasons).

Since walking speed decreases with increased ambient temperature, journey time increases between Holy Sites. This means that pilgrims are even more exposed to extreme weather conditions (i.e., a higher WBT over a more extended period of time). Therefore, even a tiny increase in ambient temperature will likely have a disproportional effect on pilgrims' health. This study identified factors affecting walking speed and journey time under hot temperatures, which can be used as inputs for planning, organising, and designing appropriate facilities.

Keywords: Walking speed, crowd flow, extreme weather, wet-bulb temperature, Heat Index.

Hot Weather Affects Crowd Movement Characteristics in the Holy Sites during the Hajj

1. Introduction to the Pilgrims Walking in Hot Weather Conditions at the Holy Sites

The Saudi National Centre of Meteorology (2024) has conducted a description in its climate study on the Makkah region, which covers historical periods of climate data and future forecasts for the Hajj seasons from 2024 to 2050. According to the survey (2024), there are noticeable changes in climate change and increased temperatures in Makkah during the Hajj season. The current and future forecasts show that the maximum temperature is projected to exceed 40°C during the Hajj seasons from 2024 to 2050, with a minimum temperature forecast of 30°C.

The Holy Sites experience extremely hot weather conditions, with an example of the maximum temperature reaching 51.8°C in the shade during the Hajj season of 1445H (2024G). This poses a significant challenge for pilgrims and operators. The risk of heat stress or heat stroke during Hajj rituals in hot weather is five times higher compared to normal conditions. It was also found that the leading causes of suffering for pilgrims in hot weather conditions are transportation issues and the need to walk long distances under the sun without shade, leading to extreme heat exhaustion. Exposure to sunlight and heat stress made walking long distances to or from camps even more difficult, as the paths were crowded and access to tents was restricted. The overcrowded roads made it hard for emergency services to reach those in need, and irregular pilgrims without shelter or transportation added to the challenges. This situation contributed to fatigue and an increase in deaths, particularly among the elderly or sick pilgrims. The pedestrian patterns among pilgrims in the Holy Sites can be categorised into four groups:

1. Regular pilgrims who walk by choice.
2. Regular pilgrims who walk due to a lack of transportation, unavailability, or stopping on the way.
3. Lost regular pilgrims.
4. Irregular pilgrims who were compelled to walk.

Table 1 shows the walking distances between the Holy Sites during the stages of Hajj rituals: Tarawih, Tassaied, Ifadah, departure from Arafat, Muzdalifah and departure from Mina. The walking distances were also calculated for the various categories of pilgrims (regular/group/elderly) who walk at different average speeds (1.0/0.5/0.25 m/sec). Irregular pilgrims are expected to be exposed to more sunlight than others due to the lack of shade or transportation. The table highlights that the most extended period pilgrims spend on the paths and open spaces is in the Arafat area.

Table 1: Walking distances and times between the Holy Sites during the Hajj season

Origin (Start)	Destination (End)	Distance (KM)	Non-Stop Walking Duration in Hours		
			v=1.0 m/sec	v=0.5 m/sec	v=0.25m/sec
Al Haram Central Area	Mina Camps	8.2	2.28	4.56	9.11
Mina (camps)	Arafat	12.3	3.42	6.83	13.67
Arafat (Nimrah)	Arafat (Jabal Al Rahmah)	2.8	0.78	1.56	3.11
Arafat	Muzdalifah	9.6	2.67	5.33	10.67
Muzdalifah	Mina (Jamarat)	5.4	1.50	3.00	6.00
Mina (Jamarat)	Mina (Camps)	3.1	0.86	1.72	3.44
Mina (Camps)	Al Haram Central Area	7.9	2.19	4.39	8.8

2. Temperature Heat Index for the risk of sunstroke and heat stress

The study in reference (Al-Maqdisi et al., 2022) shows temperatures (wet-bulb temperature) and their future projections, as well as the severity of the situation (Danger/Extreme danger) in Figure 1. The period from July to October will

experience the hottest and most humid weather conditions in the Holy Sites, which pose the most danger to humans, leading to the emergence of what is known as the "wet-bulb temperature". When conditions are hotter and more humid, the body can regulate internal temperature less through sweating, as moisture evaporates more slowly. Figure 1 indicates that the risk of heat stress and sunstroke will persist in Makkah during the Hajj seasons in the upcoming years. The wet bulb temperature is the lowest temperature at which air can be cooled by the evaporation of water in the air at constant pressure. It is measured by wrapping a wet, water-saturated wick around the bulb of a thermometer, like sweat on human skin. The wet bulb temperature is a crucial predictor of heat stress, while the dry bulb temperature represents the ambient temperature.

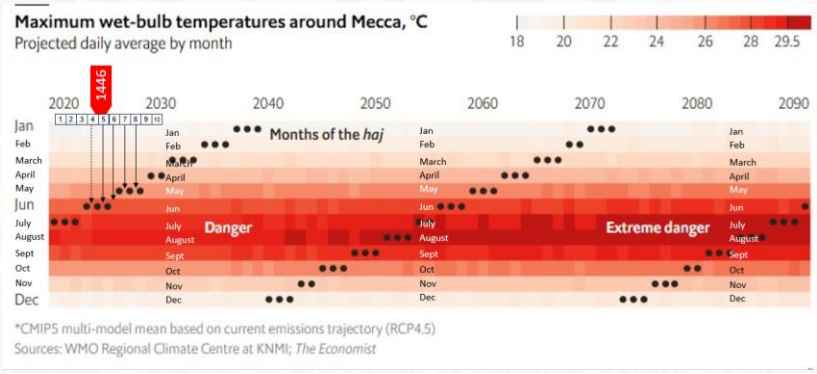


Figure 1: Expected wet-bulb temperatures during the Hajj seasons (Al-Maqdisi et al., 2022).

Figure 2 shows the Heat Index matrix contents factor of dry air temperature and humidity, recommended by the Ministry of Human Resources (2021) to classify cases and avoid the risk of injury for people performing activities in hot weather, both under the sun and in the shade. In hot and humid conditions, once sweating stops, the body is at greater risk of dehydration, heat exhaustion, and heat stroke. Heat stress can be managed immediately but can escalate to dangerous levels if not treated, if exposure to hot temperatures continues, or if fluid replacement is inadequate or unbalanced. Failure to address heat stress immediately can result in heat stroke. Heat stroke requires immediate medical attention. The emergency response should call (911) immediately, and the victim should be moved to a shaded, more relaxed area (Steadman, 197; McDonald, 2008; American Psychological Society, 2021 & Worth, 2012). Table 2 also suggests a matrix for classifying degrees of risk according to the heat index, describing the health status, ways to deal with it and the amounts of water needed to address the condition.

Table 2: Temperature index matrix containing health conditions, descriptions, and coping strategies Hazards (Recoure: Ministry of Human Resources and Social Development, 2021).

Risk degree	Heat Index* °C	Symptoms/ Illness of exposure to high Temperature	Breaks during activities	Need to water per hour
Caution	29 -25°C	Possibility of developing fatigue upon prolonged exposure or hard physical effort	Scheduled usual position	4-6 cups***
Extreme Caution	38-30°C	Possibility of muscle cramps, heat stroke, sunstroke, prolonged exposure or hard physical effort	25% of working hours divided into equal breaks	4-6 cups
Danger	51-39°C	Most properly of exposure to muscle cramps, heat stress, and sunstroke** upon prolonged exposure or hard physical effort	50% of working hours divided into equal breaks	4-6 cups
Extreme Danger	52°C +	It is about to be exposure to a sunstroke	75% of working hours are divided into equal breaks, and it is recommended that the work is suspended when the heat index reaches 56 +	4-6 cups

Heat Index المؤشر الحراري		Relative Humidity الرطوبة المرتبطة								
		10%	20%	30%	40%	50%	60%	70%	80%	90%
Air Temp °C درجة الحرارة	>50	**	**	**	**	**	**	**	**	**
	50	48	**	**	**	**	**	**	**	**
	49	47	**	**	**	**	**	**	**	**
	48	45	53**	**	**	**	**	**	**	**
	47	44	51	**	**	**	**	**	**	**
	46	43	49	**	**	**	**	**	**	**
	45	42	47	**	**	**	**	**	**	**
	44	41	46	52**	**	**	**	**	**	**
	43	40	44	49	**	**	**	**	**	**
	42	39	42	47	54**	**	**	**	**	**
	41	38	41	45	51	**	**	**	**	**
	40	37	39	43	48	**	**	**	**	**
	39	36	38	41	46	52**	**	**	**	**
	38	35	37	39	43	49	55**	**	**	**
	37	34	35	38	41	46	51	**	**	**
	36	33	34	36	39	43	48	54**	**	**
	35	32	33	35	37	41	45	50	**	**
	34	31	32	33	35	38	42	47	52**	**
	33	31	31	32	34	36	40	44	48	54**
	32	30	30	31	32	34	37	40	44	49
	31	29	29	30	31	33	35	38	41	45
	30	28	28	29	30	31	33	35	38	41
	29	27	27	28	29	30	31	33	35	37
	28	27	27	27	28	28	29	31	32	34
	27	26	26	26	27	27	28	29	30	31
	26	25	25	26	26	27	27	27	28	28

Figure 2: Heat index as a measure of critical temperature and humidity used for warning of preventive measures to reduce exposure to hot weather. Hazards (Ministry of Human Resources and Social Development, 2021).

3. Characteristics of Pedestrian Walking Speeds

3.1 Crowd Density – Flow -Speed Relation:

The crowd density (***ϱ***) Determines the crowd flow. The crowd density is the number of people per square metre, which can be measured in one area and is equal to the density per square metre for standing or moving people. The density can be calculated using the equation (eq. 1):

$$\varrho = \frac{Persons}{metre^2}$$

The following equation (eq. 2) and the curve in Figure 3 describe the relation between pedestrian density (***ϱ***) and flow (***F***). The flow rate is the number of people passing through a cross-section per meter per second. The flow of pedestrians increases as pedestrian density increases until it reaches a critical point. After reaching the critical density, the flow decreases as density increases, as shown by Weidmann (1993). This relationship depicts how walking speed decreases as density increases.

$$F = \frac{Persons}{metre/second}$$

Pedestrian speed (***v***) It is measured in metres per second and is described by the following equation (eq. 3).

$$v = \frac{metre}{second}$$

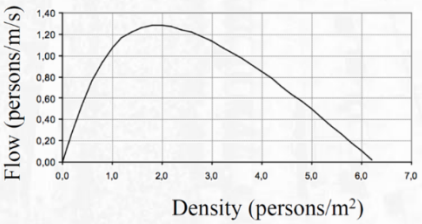


Figure 3: Relationship between flow and density (Weidmann, 1993)

3.2 Factors affecting the speed of crowd movement:

The speed at which a person walks is influenced by their step length and frequency of strides. Other factors that can affect walking speed include gender, age, height, body size, health status, time pressure, amount of luggage, time of day

(morning or evening), weather, climate and temperature, altitude above sea level, length of the walking path, degree of slope, climbing or descending stairs, surface condition of the walkway, attractiveness of the surrounding areas, and pedestrian density (Figure 4). For example, the average walking speed of men is 11% higher than women's. Differences in body size, stride dimensions, and physical performance can explain this difference. Additionally, there is a correlation between walking speed and age, as illustrated in Figure 5. In general, older individuals tend to walk at a slower pace compared to younger people. Moreover, at average densities, the speed of a group is lower than that of an individual, as depicted in Figure 6. Pedestrian speed also depends on the year's season and the time of day. It is also influenced by climate and weather conditions, ambient temperature and humidity, which affect physical performance and walking speed. Table 3 summarises the factors affecting crowd movement speed, which can be classified into three areas: crowd characteristics, external influences, and infrastructure characteristics. Pedestrian arrival goals, movement purposes, and behaviours can speed up or slow down pedestrians depending on the movement task and purpose (Tables 3 and 4). Some characteristics of speed in moderate climates can be determined as follows:

- Walking speed is set as a maximum value of 2.5 m/s.
- Running speed starts at 6.0 m/s (speed between 2.5 and 6.0 is considered a transitional stage).
- The lowest average walking speed is about 0.5 m/s.
- Pilgrims walk in groups and slower than individuals.
- The speed decreases with group movements and high C to a minimum value of 0.2 m/s
- 30% of pedestrians walk at a speed of less than 1.2 m/s.
- 1.34 m/s is considered average at a temperature of 15 °C.
- On average, men's walking speed is 11% higher than women's.
- Pedestrian speed depends on the person's stride length and frequency of steps.
- Ambient temperature and humidity affect physical performance and walking speed.

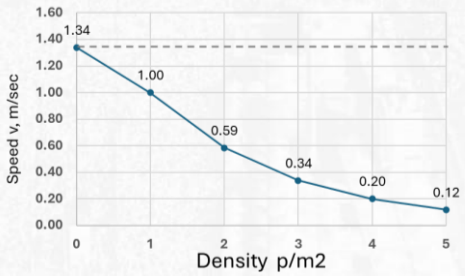


Figure 4: Relationship between density and walking speed (Buchmueller & Weidmann, 2006)

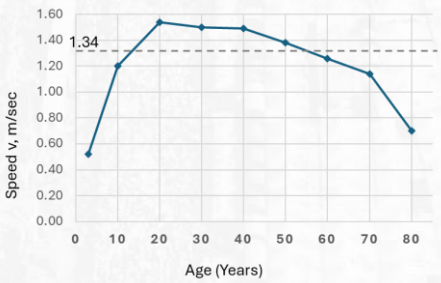


Figure 5: Relationship between Speed and age (Weidmann, 1993)

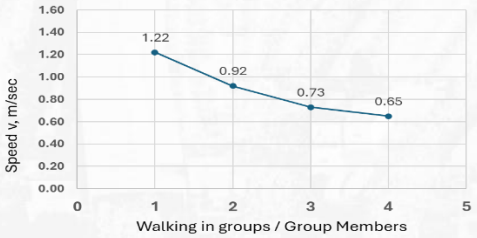


Figure 6: Speed of individual and group pedestrians (Gorrini, 2015)

Table 3: Factors affecting the speed of crowd movement (Weidmann, 1993)

Infrastructure specifications	External influences	Crowd specifications
- Slope inclination - Stairs - Condition of the track surface - Attractiveness of the surrounding areas - Pedestrian density - Intersections with vehicles	- Objective - Time of day - Weather/climate and temperature - Elevation above sea level - Length of route	- Gender (men or women) - Individuals or groups - Age - Body size - Health status - Character and emotions - Mood - Time pressure - Loads of luggage - People with disabilities - Density

Table 4: Relationship between walking speed and types and purposes of mobility (Weidmann, 1993 & Owaidah, 2023)

Purpose of the traffic	Average walking speed m/s
Daily transportation (round trip)	1.61
Work	1.34
Shopping Commercial areas	1.16
Tourism/leisure movement	1.10
Travelers (transport facilities and airports)	1.49
Sports events (youth)	1.75
Performing Hajj rituals	0.70
Pilgrim groups' delegation programs for stoning the Jamarat and Metro	1.00
Average speed for comparison (Temperature 15 °C)	1.34

3.3 Physical Effort of Pedestrians during Movement in Normal and Hot Climates and its Impact on Walking Speed:

The study of walking speed, energy consumption, and physical effort of professional athletes to achieve maximum performance during sports practices in different climates has been the focus of many references. In 1993, Weidemann evaluated the energy consumption of pedestrians during other activities and movements under various conditions, including temperature fluctuations. The results were summarised as the introductory metabolic rate (burning) for the energy consumption of humans, which consists of the total energy consumption consisting of the introductory metabolic rate (rest) and the metabolism consumed through activity (practice). The study concluded that the body's energy consumption consists of the introductory metabolic rate (energy required at rest) and the energy consumed through physical activity. The introductory metabolic rate is the energy needed by the body at rest (lying or sitting) at a temperature of about 28°C.

Energy consumption varies based on the activities practiced and peaks around the age of 19, declining sharply between 50 and 60 years of age. Walking speed affects physical energy expenditure, with climbing stairs requiring ten times more energy than walking on a flat surface. Additionally, the energy consumed when walking at a speed of up to 2.5 m/s is higher than when running. The minimum energy for walking is about 274 kJ/km at 1.34 m/s and about 250 kJ/km when running at a speed of 3.89 m/s. The dimensions of walking steps and friction are significant factors in the expenditure of physical energy, with men taking steps of 72-78 cm and women taking steps of 63-67 cm. For individuals with disabilities and patients, the step dimensions can be half those for healthy individuals (Table 5).

Table 5: The relationship between energy consumption and physical activity for men and women (Weidemann, 1993)

Energy consumption activity	**Men** (Kilo Jole/ hour)	**Women** (Kilo Jole/ hour)
Basal metabolic rate at rest	300 kJ/h	250 kJ/h.
Standing	630 kJ/h	440 kJ/h
Walking on level	760 kJ/h	630 kJ/h
Fast walking	1280 kJ/h	1280 kJ/h
Running	2730 kJ/h	2730 kJ/h
Walking on level ground with a load of 10KG	800kJ/h	660kJ/h
Walking on a ramp (slope 5%)	1150 kJ/h	1150 kJ/h
Walking on stairs	3500kJ/h	3500kJ/h

Researcher Mohamed Dridi et al. (2015) surveyed pilgrims from Africa, Asia, North and South America, and Europe. They assessed the physical condition (active, tired, very exhausted) and walking speed of the pilgrims in the Makkah Grand Mosque. The survey compared two age categories: 10-50 years and over 50 years. The results revealed a clear difference in walking speed according to age and physical condition, with a noticeable 20% drop in speed due to these factors (Figure 7).

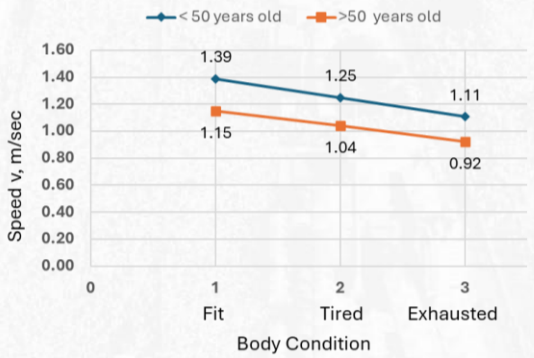


Figure 7: Measurements of the difference between walking speed according to age and physical condition (Dridi et al., 2015).

3.4 Walking speed empirical data from Mina during Hajj seasons:

Crowd-analysis cameras connected to computer-vision crowd-analysis software have been installed around the Jamarat bridge since 2007. Even though the cameras are mainly intended for real-time crowd control, they also provide a valuable historical record of crowd data spanning multiple Hajj seasons. To study the impact of ambient temperature on crowd behaviour. We have analysed the average crowd speed on three one-way pedestrianised streets in Mina (204th Street, Souq al-Arab Street, and Al-Jawhara Street). These three streets were chosen because they are major uncovered streets leading towards Jamarat and exposed to direct sunlight (Figure 8).

Furthermore, we have applied a time filter to include data only between 9 am and 3 pm, where we expect the sunshine to be extreme, and we have only included data when the low crowd density is in the range of 0.1 m^{-2} – 0.5 m^{-2}. The reasoning behind this density filter is as follows: (i) excluding data for densities < 0.1 m^{-2} since lower densities than that would likely be loitering people as opposed to pilgrims walking towards Jamarat; and (ii) excluding densities > 0.5 m^{-2}, since for higher densities than that, the pilgrims would start to reduce their walking speed due to the crowdedness as opposed to due to the heat. As expected, walking speed has significantly reduced in recent years (when the temperature is higher). The reduction is even more substantial than expected, which is likely due to two different factors: (i) pilgrims have walked for a long distance before we measure their speed, and (ii) pilgrims mainly walk in groups, which means that they need to adapt their speed to the slowest member in the group (which is likely to be elderly or mobility impaired pilgrims who are likely to suffer severely from walking long distances in high temperatures), (Figure 9).

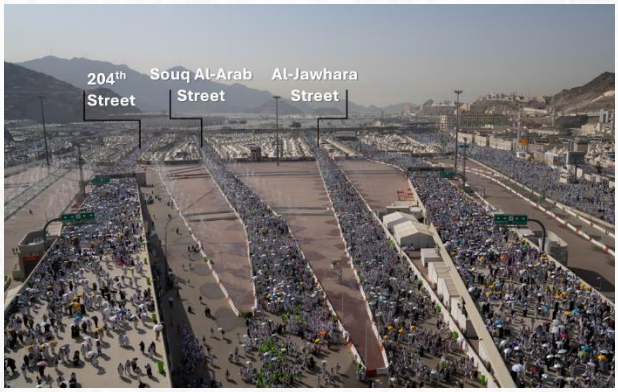


Figure 8: Placement of CCTV cameras that measure crowd density, flow and walking speed, Hajj 1445.

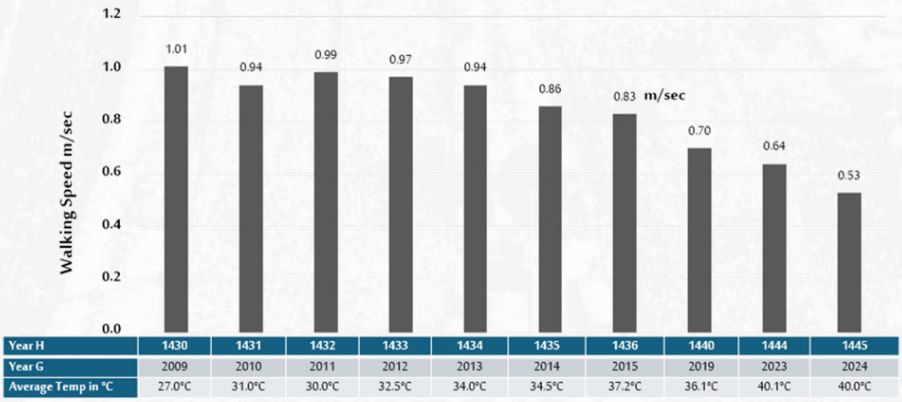


Figure 9: Average walking speed in Mina streets per Hajj season.

3.5 Characteristics of Walking under Temperature Changes

Human physical performance during outdoor activity depends on the surrounding external climate. People must maintain body temperature by managing evaporation and sweating based on humid temperature, radiation, and clothing. As the external temperature increases significantly, human performance decreases. According to Weidmann (1993), an increase in temperature from 10°C to 30°C leads to a 12% decrease in human energy output.

Figure 10 shows curve A data from different studies illustrates the relationship between walking speed and temperature. The data for curve B are measured in the three streets of Mina (see Chapter 4.3). The dot plot in Figure 10 (A) shows that walking speed is faster in wintry weather compared to hot weather. Significant temperature drops, such as transitioning from negative to positive hot temperatures, are rare in the temperature range (-15°C till +30°C; Bosina 2018. & Monheim 1980). Therefore, each trend can be tracked separately within a limited temperature range. For instance, the average

walking speed is 1.34 m/s at a temperature of 15°C, and it decreases to 1.20 m/s when the temperature rises to 25°C, representing a 10% decrease. According to values from Chen et al. (2023), there is a 15% decrease in walking speed when the temperature changes from 25°C to 35°C. By considering all the values in Figure 10 and averaging them, we can estimate that a temperature increases from 20°C to 35°C leads to approximately a 13% decrease in walking speed. Nevertheless, if we look at walking speed and changes in hot temperatures, such as in the Holy Sites during Hajj in recent years (in the range of 25°C to 50°C), we will find a significant drop of more than 50% in walking speed.

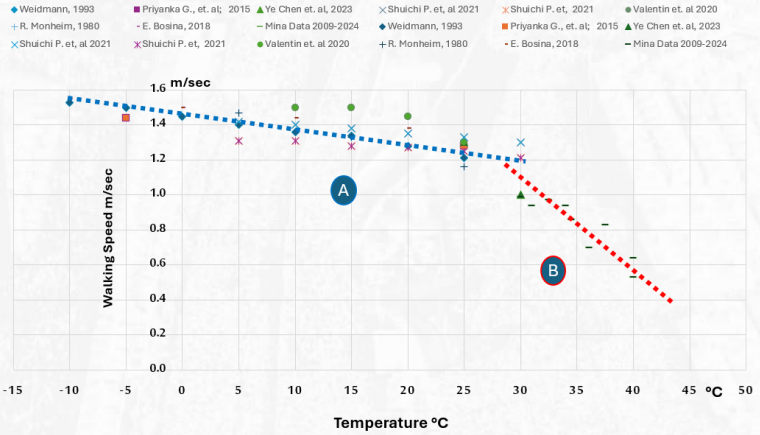


Figure 10: Relationship of pedestrian speed to temperature from different references

In a research study by Valentin et al. (2020) on heat stress during walking, the researchers compare the condition of pedestrians in 31 countries. They set the typical walking distance for all countries at 500 metres, the average annual hot temperature in the city, and relative humidity at 60%. It has been shown that there is a general relationship between temperature and walking speed. For example, in countries with cold winters, such as Ireland and the Netherlands, the walking speed is 1.63 m/s at an average of 14°C, which is higher than in hot weather countries like Jordan and Brazil, where the walking speed is 1.15 m/s at an average temperature of 25°C.

There is a lack of global research on the effect of hot temperatures on walking speed. Existing studies have focused on temperatures in countries with wintry weather. The physical ability of a person to walk long distances depends on the temperature of the surrounding environment, air humidity, and heat emission from the human body. In a study by Gupta et al. 2015, the walking speed of pedestrians in Toronto, Canada, was measured in winter temperatures and compared to summer temperatures. The aim was to establish criteria for designing pedestrian paths and evaluating pedestrian flows for shopping and other activities. The results showed that people walk 11% faster in wintry weather (at -5°C at a speed of 1.44 m/s) than in summer weather (25°C, 1.28 m/s); see also Figure 10 for more details.

In the study by Chen et al. (2023), the walking speed was measured in a public park in China under different conditions and temperatures. The results showed that visitors walked at different speeds depending on the surrounding activities and temperatures. Specifically, the study found that the walking speed was measured at 1.30 m/s when the temperature was below 28°C and at 1.03 m/s when the temperature was above 32°C, indicating a 20% decrease in the latter case (Figure 10). In a study referenced by Shuichi et al. (2021), the relationship between ambient conditions (ranging from -5°C to 35°C) and walking speed for men and women was studied. The measurements showed that women's step dimensions are smaller than men's and that walking speed decreases by about 3.5% with increasing temperatures (Figure

10). Weidmann (1993) presented research on the relationship between the physical energy expended by humans during walking activities under varying ambient conditions (ranging from -10°C to 25°C) and the facilities' topography. Based on the average walking speed on a flat surface of 1.34 m/s at a temperature of 15°C, the study found that when the temperature rises to 25°C, the speed decreases to 1.20 m/s, representing a 10% reduction (Figure 10).

4. Results and Discussion on the Impacts on Walking Speed

- **Crowd density**: The density of pedestrians significantly impacts crowd speed. As pedestrian density increases, walking speed and flow decrease. Figure 3 shows that when there is one person per square meter, the walking speed is 1.0 m/s. However, when the density increases to 4 people/m2, the speed decreases to 0.2 m/s, an 80% decrease.
- **Walking in groups:** The measurements in Figure 5 illustrate how walking speed is affected by the number of individuals walking together, whether an individual, a pair, a group of three, or a group of four. The data shows that speed decreases as the group size increases; for example, there is a 30% decrease when the group size increases from 2 to 4. It is important to note that the local density criterion, not the average, remains the primary and effective measure of walking speed.
- **Ages of pilgrims:** Statistics show that one-third of the pilgrims are over 55 years old. Figure 6 illustrates how age affects walking speed due to physical and health conditions and the decrease in step dimensions for the elderly compared to the youth. Pilgrims who perform the Hajj rituals are generally under 65 years old, as those above this age are considered to have special needs. The change in speed is limited to a 15% decrease from the average walking speed. This is also depicted in Figure 11, which measures the effect of age on walking speed and the difference between ages under and over 50 years.
- **Gender:** Men and women have different walking speeds. On average, men walk 11% faster than women. This is mainly due to men's larger average body size and men taking longer steps than women. As a result, men cover more distance in a given amount of time.
- **The physical energy exerted by pedestrians:** The introductory metabolic rate (burning) of a person's energy consumption consists of the total energy consumption formed by the introductory metabolic rate (rest) and the metabolism consumed through activity (practical). Humans typically reach their maximum physical performance at around twenty years old, with performance declining as they approach 55 years of age. It has been shown that body size, walking stride dimensions, and access to walking facilities are the main factors affecting physical energy expenditure, mainly when covering long distances. When comparing physical effort at different temperatures, it was observed that energy expenditure decreased by about 12% as the temperature increased. In a study conducted at the Makkah Grand Mosque, samples of pilgrims showed a correlation between physical condition (active, tired, very exhausted) and walking speed, with a noticeable 20% decrease in speed between age groups (under 50 and over 50 years) due to differences in age and physical condition (see Figure 7). Medical references have also demonstrated that walking speed may decrease by half in sick individuals, and carrying luggage increases the effort expended while walking.
- **Infrastructure walking paths:** Walking up or down stairs reduces walking speed by about half compared to walking on flat surfaces. The recommended slope for pedestrian ramps is 5%, and there is no noticeable effect on pedestrian speed for distances on slopes less than 100 metres. However, when walking distances of hundreds of metres on

slopes, walking speed may decrease by up to 20%. The condition of the walkway surface also affects the friction of the steps and the physical effort exerted, which can slow down the walking speed.

- **Pedestrian crossings and interactions with vehicles:** Vehicles at intersections force the crowd to form groups that start and stop at intervals according to the traffic conditions. This directly affects the level of service (LOS) and reduces the speed by about 10% (HCM2000, 2020).
- **Weather, climate, and temperature:** Weather conditions, such as ambient temperature and humidity, directly affect physical performance and walking speed. In wintry weather, walking speed is faster compared to hot weather. As the temperature rises (averaging interval ten °C to 20°C), walking speed decreases by up to 15%. Walking under the sun and high temperatures above 30°C degrees, like in the Holy Sites in Makkah, causes fatigue and energy expenditure, which leads to exhaustion, shortening walking steps and reducing speed. If we add the temperature rise from 30°C (night) to 50°C (day) degrees, this may cause a decrease in walking speed to more than 50%.

5. Estimation of the Walking Speed in the Holy Sites in Hot Weather

The walking speed in the Holy Sites area decreases by more than 50% during the Hajj season when the temperature rises significantly, from 30°C to above 50°C. This decrease is due to the combined effects on pilgrims during the performance of their rituals. Many pilgrims walk long distances, several kilometres, for lengthy periods (3-4 hours) under the sun, exerting great physical effort. Additionally, many are over 55 years old, have a health condition requiring care, and walk in groups. The rate of decrease in walking speed in the Holy Sites can be evaluated from the most important influencing factors in the mentioned section. Table 6 shows the most important influencing factors on walking speed during Hajj with the estimated weight on the walking speed.

Table 6: The most important influencing factors on walking speed during Hajj

Factor Δ_n	Max Speed decreasing Δ	Estimated Weight
Crowd Density Δ_1	80%	100%
Body condition Δ_2	20%	25%
Weather conditions Δ_3 cases 1 wintertime	15%	25%
Weather conditions Δ_3 cases 2 summertime	50%	75%
Age Δ_4	6%	10%

The actual walking speed can be calculated as:

$$\text{Actual Walking Speed:} \quad v = (1- \Delta_n) * v_{origin}$$

By estimating the effect of these four factors in the same place and time (table 6), we can adapt the impact of the decrease in walking speed (Δ) using the following equation (case 1):

$$\Delta n = \frac{0.8*1.00+0.2*0.25+0.15*0.25+0.06*0.10}{4} = 0.23 \ = (23\%)$$

For example, walking speed was adopted in the scheduling programme for pilgrim groups to Jamarat and transport by Al Mashaaer Metro (Haase et al., 2016), which had a value of 1.0 m/s. Therefore, if the four factors from the table 6 are present, the walking speed (Δn) should be reduced by 23%:

The actual walking speed for the scheduling programme is: $v = (1- \Delta_n) * v_{origin} = (1.0- 0{,}23) * 1.00$ m/sec = 0,77m/sec

The actual walking speed for the scheduling programme for case 2 in the hot summertime:

$$\Delta n = \frac{0.8*1.00+0.2*0.25+0.50*0.75+0.06*0.10}{4} = 0.31 \ = (31\%)$$

The actual walking speed in case 2 is: $v = (1- \Delta_n) * v_{origin} = (1.0- 0,31) * 1.00$ m/sec = 0,71m/sec.

6. Conclusion

This study provides a comprehensive analysis of the impact of high temperatures on pedestrian flow characteristics during the Hajj in Makkah. The current and future forecasts show that the maximum temperature is projected to exceed 40°C (min. average 30°C) during the Hajj seasons in Makkah. The risk of heat stress or heat stroke during Hajj rituals in this hot weather is five times higher than usual. The Heat Index matrix, which contains dry air temperature and humidity factors ('wet bulb temperature ' (WBT)), is used to classify cases and avoid the risk of injury for people performing activities in hot weather.

Walking speed can be expressed as a function of crowd density. Larger crowd densities reduce the ability to move freely, leading to lower walking speeds. The combination of meta-analysis of previous relevant studies and our analysis of pilgrim walking speed measurements in the Mina area over several Hajj seasons allows the evaluation of the impacts on walking speed. The density of pedestrians had a significant effect on crowd speed. The study showed that when the density increases to 4 people/m2, the speed decreases by 80%.

The second factor affecting the walking speed and journey time under hot temperatures can be used to plan, organise, and design appropriate facilities. Walking under the sun and high temperatures above 30°C degrees, like in the Holy Sites in Makkah, causes fatigue and energy expenditure, which leads to exhaustion, shortening walking steps and reducing speed. If we add the temperature rise from 30°C (night) to 50°C (day) degrees, this may cause a decrease in walking speed to more than 50%. The third main impact is infrastructure conditions (flat surfaces, stairs, ramps), where walking speed on stairs could be reduced by about half compared to walking on flat surfaces. Other factors, such as pilgrims' ages, gender, physical energy exerted by walking, and vehicle interactions, can decrease walking speed by up to 20%. Generally, considering all the above factors, the walking speed in the Holy Sites area decreases by more than 50% during the Hajj season when the temperature rises significantly, from 30°C to above 50°C. The study proposed a methodology for considering the factors to calculate the applicable speed for crowd movement design and organisation.

Future research should focus on developing predictive models for pedestrian flow under varying temperature conditions and exploring innovative solutions to enhance the comfort and safety of pilgrims during extreme weather events. Implementing these strategies will be crucial to ensuring the well-being of pilgrims in the coming years as global temperatures continue to rise.

7. Recommendations

The meta-analysis of international studies and our measurements during the Hajj seasons showed a direct relationship between ambient temperature and walking speed. Walking speed may decrease by as much as 50% in high-temperature conditions. Therefore, we suggest the following measures to deal with the movement of pilgrims in hot weather conditions in the Holy Sites:

- The walking distances in the Holy Sites must be reduced by providing comprehensive and safe crowd movement plans, which include the shortest walking paths to the transport hubs, accommodations, Jamarat and the Grand Mosque.
- Sufficient transportation must be supplied to transport the pilgrims without long waiting times.
- Scheduling programs need to be developed to dispatch groups of pilgrims to perform the Hajj rituals at appropriate times and routes to minimize the impact of high ambient temperatures.

- The participation of irregular pilgrims in the Hajj must be limited because they lack accommodation and transportation and are most exposed to the sun and heat stress.
- The walking paths in Arafat, between Muzdalifah and Mina, in Mina and on the roads of the Grand Mosque should be shaded and equipped with water sprays to cool the atmosphere, abundant drinking water stations, health services, and toilets alongside the walking paths.
- The authorities responsible should provide awareness and guidance programs for pilgrims and operators about the risks of hot weather conditions and the services available in typical and emergencies.
- The necessity of conducting scientific, health and architectural research to develop a suitable environment for performing the Hajj rituals in the Holy Sites under hot weather conditions.

References

- "دراسة مناخية على منطقة مكة المكرمة للفترات التاريخية والتوقعات المستقبلية خلال مواسم الحج"2024-2050. The National Centre of Meteorology/Climate Change Centre. (2024). Available at: https://hikersbay.com/climate-conditions/saudiarabia/mecca/climate-conditions-in-mecca.html?lang=en.
- Al-Maqdisi, et al. (2022). "How will the haj change as global temperatures rise?" *The Economist*, December.
- Ministry of Human Resources and Social Development. (2021). "Procedural Guidelines for Occupational Safety and Health for Preventing the Effects of Exposure to Direct Sun and Heat Stress."
- Steadman. (1979). "The Assessment of Sultriness. Part I & II: A Temperature-Humidity Index Based on Human Physiology and Clothing Science."
- McDonald Oliver F., et al. (2008). "Heat Stress Improving Safety in the Arabian Gulf Oil and Gas Industry." *Journal Paper*, Paper Number: ASSE-08-08-31, August 1.
- American Psychological Society. (2021). "EXERCISE UNDER HEAT STRESS: THERMOREGULATION, HYDRATION, PERFORMANCE IMPLICATIONS, AND MITIGATION STRATEGIES." *Physiological Review. *
- Worth, Tammy. (2012). "How to Exercise Safely in the Heat." *Healthline. * Available at: https://bit.ly/2NLLXB0.
- Weidmann, U. (1993). "Transporttechnik der Fussgänger, Transporttechnische Eigenschaften des Fussgängerverkehrs." Schriftenreihe des IVT Nr. 90, ETH Zurich, March.
- Buchmueller, S., & Weidmann, U. (2006). "Parameters of Pedestrians, Pedestrian Traffic and Walking Facilities." IVT-Report Nr. 132, Swiss Federal Institute of Technology Zurich.
- Gorrini, A., et al. (2015). "Empirical Investigation on Pedestrian Crowd Dynamics and Grouping." *Research Gate. *
- Owaidah, et al. (2023). "Transport of pilgrims during Hajj: Evidence from a discrete event simulation study." *Plos One, * The University of Western Australia.
- Dridi, Mohamed H., et al. (2015). "List of Parameters Influencing the Pedestrian Movement and Pedestrian Database." University of Stuttgart, Institute für Theoretische Physik, Germany.
- Bosina, E. (2018). "A New Generic Approach to the Pedestrian Fundamental Diagram." Institute for Transport Planning and Systems, ETH Nr. 25414.
- Monheim, R. (1980). "Fußgängerbereiche & Fußgängerverkehr in Stadtzentren in der Bundesrepublik Deutschland." Heft 64, ISBN 3-427-76141.
- Chen, Ye, et al. (2023). "Thermal–Acoustic Interaction Impacts on Crowd Behaviors in an Urban Park." *MDPI. *
- Valentin Melnikova, R., et al. (2020). "The impact of the pace of life on pedestrian heat stress: A computational modelling approach." *Environmental Research. *
- Gupta, Priyanka, et al. (2015). "Effects of Temperature and Time of Day on Pedestrian Walking Speed." Toronto Rehabilitation Institute, ICADI.

- Shuichi, P., et al. (2021). "Walking is regulated by environmental temperature." *Scientific Reports. * Available at: www.nature.com/scientific reports.
- Fan, Yichun, et al. (2023). "Intraday adaptation to extreme temperatures in outdoor activity." *Scientific Reports. *
- HCM2000, (2020). Transportation Research Board. *Highway Capacity Manual HCM 2000. * USA
- Haase, K., Al-Abideen, H. Z., Al-Bosta, Salim, Kasper, Mathias, Koch, Matthes, Müller, Sven, Helbing, D. (2016). "Improving Pilgrim Safety During the Hajj: An Analytical and Operational Research Approach." *Interfaces. *

Saudi Arabia's Response to Global Pandemics: Strategies for Sustainable Health and AI-Driven Solutions

Ilham T M Qattan

Taibah University

استجابة المملكة العربية السعودية للأوبئة العالمية: استراتيجيات الصحة المستدامة والحلول القائمة على الذكاء الاصطناعي

إلهام بنت طلعت بن محمود قطان

جامعة طيبة

Abstract

This review examines Saudi Arabia's strategies for managing global pandemics, focusing on responses to H1N1, MERS-CoV and specifically COVID-19. As an important pilgrimage center, the country faces unique challenges in controlling viral outbreaks during mass gatherings. The review identifies a significant research gap in integrating advanced technologies, especially artificial intelligence (AI) into public health strategies. The main objective is to evaluate how AI-driven solutions can enhance pandemic preparedness and response, considering the Kingdom's socio-religious context. This review employs a comprehensive literature analysis of studies published between 2018 and 2024, focusing on Saudi Arabia's pandemic management and the role of AI in improving health outcomes. Data was sourced from databases such as PubMed and Google Scholar and thematic analysis was used to synthesize findings. Saudi Arabia's proactive measures, including lockdowns, mass testing and vaccination campaigns significantly mitigated pandemic impacts. The integration of AI technologies, such as predictive models and telemedicine, improved diagnostic accuracy, resource allocation and overall health outcomes. Despite the successes, challenges remain in fully implementing AI solutions and addressing ethical concerns. The review concludes that while Saudi Arabia has demonstrated effective pandemic management, continuous advancements in AI and other technologies are essential for future preparedness. Strengthening these capabilities will enhance global health security and provide a model for other nations in managing pandemics. Future research should address implementation challenges and explore ethical considerations to fully influence AI's potential in public health.

Keywords: COVID-19, Artificial intelligence, Machine Learning, Telemedicine, Immunization Programs, Influenza A virus H1N1 Subtype, Middle East Respiratory Syndrome Coronavirus, Preventive Health Services

1. Introduction

Saudi Arabia, as a global hub for millions of pilgrims, has encountered multiple significant viral outbreaks. In 2009, the H1N1 influenza pandemic also known as swine flu led to strict control measures, especially during the Hajj pilgrimage. The country became the epicenter of the Middle East Respiratory Syndrome Coronavirus (MERS-CoV) in 2012, a zoonotic

virus with a high mortality rate that caused several outbreaks (Memish et al., 2020). The COVID-19 pandemic caused by the SARS-CoV-2 virus reached Saudi Arabia in March 2020, influencing the government to implement strict public health measures, including lockdowns, travel restrictions, suspension of religious pilgrimages and a large-scale vaccination campaign. These recurrent outbreaks have extremely impacted public health, demanding comprehensive strategies for infectious disease management and control (Elkhatib et al., 2022).

The necessity for effective public health responses to viral outbreaks in Saudi Arabia is highlighted by the region's distinct social, economic and religious contexts. As a global pilgrimage center, especially during Hajj, Saudi Arabia faces increased vulnerability to viral outbreaks such as MERS-CoV and COVID-19. The nation's public health infrastructure must efficiently manage these threats to prevent extensive transmission, especially in densely populated religious events. Strict measures such as quarantine, vaccination drives and ensuring community adherence are significant for safeguarding public health (Wilder-Smith & Freedman, 2020). These strategies not only protect the Saudi population but also have significant global health implications, given the international scope of religious pilgrimages (Alhazmi et al., 2019).

Saudi Arabia's management of public health crises, notably during the COVID-19 pandemic, emphasizes on the significant role of swift and coordinated interventions in controlling viral outbreaks. The country effectively utilized extensive testing, contact tracing and enforced social distancing by adopting a "whole government" approach aligned with WHO guidelines. This strategy, along with high public awareness, significantly restrain virus transmission and minimized case severity (Chiu et al., 2023). The prompt distribution of healthcare resources, despite challenges such as supply demands and the complexities of restrictive measures, was essential in maintaining low mortality rates and reducing the pandemic's broader socio-economic and political impacts (Kontis et al., 2020). Saudi Arabia's experience highlights the significance of strong and adaptive public health responses in effectively handling viral infections and can serve as a model for other nations facing similar challenges (AlFattani et al., 2021).

Saudi Arabia's essential role in the Islamic world is significantly influenced by its management of the two holy mosques and its organization of the annual Hajj and Umrah pilgrimages. The Kingdom’s capacity to accommodate millions of pilgrims annually highlights its important function in facilitating a unique global gathering that promotes international relations, dialogue and cultural exchange. The importance of international collaboration is highlighted by the need to manage health crises, as exemplified during the COVID-19 pandemic. The pandemic highlighted the necessity for strict health protocols and travel restrictions to protect pilgrims, exhibiting the need for global cooperation in addressing health emergencies (Gössling et al., 2020). Saudi Arabia’s implementation of restrictive measures and diligent health checks during Hajj emphasizes on its dedication to maintaining pilgrim safety while addressing both religious duties and public health concerns (Alammash et al., 2021).

Artificial Intelligence (AI) and advanced technologies are essential in pandemic management, enhancing healthcare responses and crisis management through improved decision-making and resource allocation. Artificial intelligence systems enable accurate diagnosis, timely interventions, and optimal healthcare resource management by analyzing large data sets. Also the work on epidemiological assessment using mathematics and equations, such as the SEIQR epidemiological model, which relies on dynamic analyzes including the new reproductive number and detailed stability analysis (Youssef et al; 2021), these systems can predict disease outbreaks, monitor the spread of infection, and improve treatment strategies (Syrowatka et al., 2021). Furthermore, AI aids in the development of personalized medicine, creating individualized treatment plans based on patient-specific data. Overall, integrating AI into healthcare with dynamic

epidemiological assessment using the algorithmic epidemiological analysis models enhances the control and response efforts, leading to better patient outcomes and more adaptive healthcare systems (Abdo, 2024).

The review emphasizes on the importance of developing strong and adaptable public health strategies to effectively address recurrent viral outbreaks. Saudi Arabia's experiences with H1N1 Influenza, MERS-CoV and COVID-19 exhibits the necessity for ongoing advancements in public health crisis management, especially given the challenges posed by large-scale religious gatherings. It highlights that the incorporation of advanced technologies, such as artificial intelligence, into pandemic response frameworks can substantially improve diagnostic precision, optimize resource allocation and enhance overall health outcomes. By analyzing past responses and evaluating emerging technological innovations, the review provides valuable insights for strengthening Saudi Arabia's preparedness for global health crises and demonstrates the potential of AI-driven solutions to strengthen public health infrastructures on a global scale.

The recurring viral outbreaks in Saudi Arabia, including H1N1 influenza, MERS-CoV and COVID-19 pandemic, emphasizes the essential need for strong and sustainable public health strategies tailored to the nation's unique socio-economic and religious context. Despite effective government interventions, such as lockdowns, mass testing, travel restrictions and vaccination campaigns, the challenge of managing health risks during massive religious gatherings such as Hajj and Umrah persists, highlighting a significant research gap in developing more resilient health systems. However, the potential of AI-driven solutions to predict outbreaks, monitor disease spread and optimize healthcare resource allocation has not been fully explored or implemented within the Saudi context. The main objective of this review is to explore AI-driven solutions and sustainable health strategies to enhance Saudi Arabia's preparedness and response to global pandemics, ensuring the safety of both its population and millions of international pilgrims. Moreover, the review seeks to develop sustainable, technology-driven strategies that strengthen Saudi Arabia's pandemic response capabilities and contribute to global health security .

2. Methodology

2.1 Search Strategy

In this review, the author utilized previous 7-year researches that were published in peer-reviewed journals. Data was searched on widely used databases such as PubMed, NIH and Google Scholar. Time frame filters were then applied to improve the review. In order to conduct this review, data was collected with a specific focus on publications released between 2018 and 2024 investigating Saudi Arabia's response strategies to global pandemics for sustainable health and AI-Driven solutions. As indicated in Table 1 below, the author chose particular search approaches in order to obtain the data.

Table 1: Search Strategies (Source: Author)

S. No.	Search Strategy
1	("Saudi Arabia") AND ("Global Pandemics") AND ("Sustainable Health Strategies") OR ("AI-Driven Solutions")
2	("COVID-19") AND ("Public Health Measures") OR ("AI in Healthcare") OR ("Role of Media in Pandemic Management") OR ("Role of AI in Pandemic Management") OR ("AI for predicting virus outbreaks") OR ("AI-Driven Predictive Models") OR ("database updates and tracking of individuals with AI")
3	("Telemedicine") AND ("remote care initiatives") OR ("Biometric Identifiers") AND ("Global Health Security") AND ("Epidemic Control") OR ("resource allocation for managing pandemics") OR ("AI in drug discovery and Vaccine Development")
4	("Impact of Pandemics on healthcare systems") OR ("Vaccination campaigns") AND ("Quarantine") OR ("lockdowns") AND ("social distancing measures") AND ("Saudi Arabia's Vision 2030") OR ("Personalized medicine using AI") OR ("effectiveness of AI tools")

2.2 Selection Criteria

Table 2 represents the inclusion and exclusion criteria of the studies that were utilized to review, focusing on Saudi Arabia's response strategies to global pandemics for sustainable health and AI-Driven solutions.

Table 2: Inclusion and Exclusion Criteria (Source: Author)

Inclusion Criteria	Exclusion Criteria
Studies that were published in journals with peer-reviewing policies provided by the publishers were included.	Studies that were published in journals with peer-reviewing policies not provided by the publishers were excluded.
The studies included in the review were selected based on having the keywords Saudi Arabia, Global Pandemics, Sustainable Health and AI.	The studies not having the specific keyword Saudi Arabia, Global Pandemics, Sustainable Health and AI were excluded from the review.
The studies published in the last 7 years from 2018 to 2024 were included in this review.	The studies performed or papers published prior to 2018 were excluded.
Only studies that were accessible in full-text format for the public view were included.	Studies not accessible in open access format in any authorized database were excluded.

2.3 Data Analysis

14 studies were selected based on their titles, publishers and main objective of the review aligned with the current study's rationale. The analysis of the obtained data from the 14 articles was conducted using thematic analysis as presented in the discussion. The data was obtained by utilizing recurrent keywords in the paper such as Saudi Arabia, Global Pandemics, Sustainable Health and AI.

2.4 Quality Assessment

The review addresses the study quality based on the Saudi Arabia's response strategies to global pandemics for sustainable health and AI-Driven solutions. It includes the criteria on which the chosen publications were most relevant to the review aim and were published between 2018-2024. Availability of full-text studies was another important requirement that was given priority. These criteria contribute to the quality and reliability of the synthesized data by developing discussions and conclusions on the efficacy of the studies included in this review. The review's main objective is to provide a thorough understanding of Saudi Arabia's response strategies to global pandemics for sustainable health and AI-Driven solutions while incorporating the most recent data into consideration.

3. Result

Table 3 outlines the included researches and provides insights into the Saudi Arabia's response strategies to global pandemics for sustainable health and AI-Driven solutions,

Table 3: Included Studies

S. No	Author	Journal	Title	Objective	Results
1	(Yezli & Khan, 2020).	Travel medicine and infectious disease, 37, 101692.	COVID-19 social distancing in the Kingdom of Saudi Arabia: Bold measures in the face of political, economic, social and religious challenges.	To evaluate the effectiveness of strict social distancing measures implemented by Saudi Arabia to control COVID-19 transmission, considering the country's unique socio-cultural and religious context.	Early and decisive social distancing measures, including the suspension of mass gatherings and curfews, were implemented despite significant socio-economic and religious challenges; their impact on the epidemic curve and global COVID-19 response is ongoing.
2	(Alzahrani et al., 2020).	Journal of infection and public	Forecasting the spread of the COVID-19 pandemic in Saudi	The objective of this study was to forecast the daily number of COVID-19 cases in Saudi Arabia	The ARIMA model demonstrated the best performance, predicting a potential rise to 7,668 new cases per day and over

		health, 13(7), 914-919.	Arabia using ARIMA prediction model under current public health interventions.	over the next four weeks using various prediction models, including ARIMA.	127,129 cumulative cases, indicating a need for extreme precautionary measures to prevent a significant surge in infections.
3	(Aljadeed et al., 2021).	In Healthcare (Vol. 9, No. 3, p. 290). MDPI.	The impact of COVID-19 on essential medicines and personal protective equipment availability and prices in Saudi Arabia.	To assess the impact of the COVID-19 pandemic on the availability of essential medicines and personal protective equipment (PPE) in Saudi Arabia's healthcare supply chain.	The study revealed significant shortages in essential drugs and PPE, with around 51% of participants reporting shortages of key medications and 33% reporting PPE shortages. Despite these challenges, the overall impact on drug prices was minimal and effective procurement and exchange programs helped manage the disruptions.
4	(Amamou & Ben-Ahmed, 2023).	Journal of Infection and Public Health, 16(10), 1650-1658.	Managing the COVID-19 pandemic in thirty-two policy measures in Saudi Arabia: a mixed-methods analysis.	To evaluate the effectiveness of Saudi Arabia's preventive measures in controlling the spread of COVID-19 over a 590-day period from January 2020 to August 2021.	Among 32 measures, only three significantly reduced COVID-19 spread: massive community testing, complete national curfew and removal of slum areas, with varying levels of impact and statistical significance.
5	(Kaliyadan et al., 2020).	Cureus, 12(12).	Telemedicine practice in Saudi Arabia during the COVID-19 pandemic.	The study aimed to evaluate licensed physicians' attitudes and behaviors toward telemedicine during the COVID-19 pandemic.	Of 392 responses, 58.1% had used telemedicine platforms such as WhatsApp and Zoom, with strong agreement on its benefits for reducing outpatient visits and monitoring chronic patients, although concerns about technological limitations and diagnostic reliability were noted.
6	(Hassounah et al., 2020).	Journal of medical Internet research, 22(9), e19338.	Digital response during the COVID-19 pandemic in Saudi Arabia.	To highlight how Saudi Arabia utilized digital technology across various sectors during the COVID-19 pandemic, focusing on public health, healthcare services, education, telecommunications, commerce and risk communication.	Saudi Arabia developed and launched around 19 apps and platforms for public health and healthcare services, continued education through electronic learning and maintained effective risk communication through social media and SMS.
7	(Beck et al., 2018).	Global health action 11, no. 1 (2018): 1440782.	"Developing and implementing national health identifiers in resource limited countries: why, what, who, when and how?."	The objective of this study was to provide practical guidance for developing and implementing National Health Identifiers (NHIDs) to enhance health information systems and person-centered services, aligning with Sustainable Development Goals.	The study concluded that effective NHID systems, supported by strong civil protections and integrated with health services, are essential for improving health outcomes and monitoring health service impact, requiring political will and stakeholder collaboration.
8	(Alamri et al., 2022)	International Journal of Environmental Research and Public Health, 19(24), 16676.	Perception of healthcare providers during the COVID-19 pandemic: a mixed method survey in an integrated healthcare delivery system in Saudi Arabia.	This study aimed to assess the perceptions of telemedicine among healthcare professionals in Saudi Arabian military hospitals, focusing on the usefulness, ease and behavioral intention associated with teleclinic practices implemented during COVID-19.	The study revealed significant correlations between perceived usefulness and ease with behavioral intention ($r = 0.877$, $p = 0.05$), and identified these factors as predictors of teleclinic adoption ($R^2 = 0.777$, $p = 0.001$), highlighting the positive reception and the need for ongoing improvements in telemedicine practices.

9	(Bagabir et al., 2022).	Journal of Infection and Public Health, 15(2), 289-296.	Covid-19 and Artificial Intelligence: Genome sequencing, drug development and vaccine discovery.	To elucidate the role of AI in genomic sequencing, drug development and vaccine creation for COVID-19, while identifying its advantages and challenges.	AI successfully identified SARS-CoV-2 sequences and variants, facilitated drug repurposing and supported vaccine development using bioinformatics and machine learning, though challenges include data collection, validation, and model interpretability.
10	(Khan et al., 2021).	Risk Management and Healthcare Policy, 3923-3934.	The role of digital technology in responding to COVID-19 pandemic: Saudi Arabia's experience.	This study aimed to evaluate the effectiveness of various technological tools, particularly the Tawakkalna application, in managing and mitigating the impact of COVID-19 in Saudi Arabia.	Following the implementation of the Tawakkalna app and other technologies in Al Madinah Al Mounawarah, active daily COVID-19 cases decreased by 61%, demonstrating the effectiveness of digital tools in pandemic management.
11	(Baz et al., 2020).	International Journal of Intelligent Engineering & Systems, 13(5).	A Framework of Computational Model for Predicting the Spread of COVID-19 Pandemic in Saudi Arabia.	To develop a computational model using the Fuzzy-AHP technique to gauge the spread of COVID-19, predict vulnerable regions and analyze the impact on societal factors.	The proposed Fuzzy-AHP model was revealed to be the most effective among seven compared models, providing valuable insights for prioritizing countermeasures against COVID-19.
12	(Chamola et al., 2020)	Ieee access, 8, 90225-90265.	A comprehensive review of the COVID-19 pandemic and the role of IoT, drones, AI, blockchain, and 5G in managing its impact.	To view the major aspects of the COVID-19 pandemic, including its health implications, global economic impact and the role of emerging technologies such as IoT, UAVs, blockchain, AI and 5G in mitigating its effects.	The study highlights the rapid spread of COVID-19, the strain on healthcare systems and the proliferation of misinformation, while demonstrating how technologies such as AI and IoT can aid in managing and mitigating the impact of the pandemic.
13	(Chowdhury et al., 2021).	Journal of Medicine and Life, 14(3), 347.	Transformation of health care and the new model of care in Saudi Arabia: Kingdom's Vision 2030.	To evaluate the new Model of Care (MOC) as part of Saudi Arabia's health care transformation under Vision 2030, focusing on its alignment with the Kingdom's strategic goals.	The MOC introduces forty-two interventions across six systems of care, aiming to modernize and streamline the Saudi health care system in alignment with Vision 2030, ultimately enhancing the efficiency and effectiveness of health services
14	(Youssef, et al.,) 2022)	Alexandria Engineering Journal, 61(3), pp.2456-2470	A proposed modified SEIQR epidemic model to analyze the COVID-19 spreading in Saudi Arabia.	To modified SEIR model in the study submitted by Youssef and partners in 2020, 2021, and 2022 were able to conduct successful analyzes of the spread of epidemics such as Covid-19 the studies provided the "ideal protocol" for the basic steps that enabled the Kingdom of Saudi Arabia to slow the spreading and of Covid-19.	The SEIQR model's used to study of the basic disease dynamics of the emergence of Covid-19 , was based on the use of theoretical data from the Kingdom of Saudi Arabia included a reproduction number study and practice analysis from the new version of SEIQR dynamics and the used of Jacobian linear processes, In the stdy the calculation of the reproduction number by using Lyapunov stability theory to see how successful the proposed SEIQR model was. The researchers concluded that the new proposed SEIQR model is effective to montir the spread of epidemics of Coronavirus (COVID-19).
15	(Nooh et al., 2021).	Journal of Public Health, 29, 1107-1114.	Public awareness of coronavirus in Al-Jouf region, Saudi Arabia.	This study aimed to evaluate the level of awareness about MERS-CoV among the population in Al-Jouf region, Saudi Arabia,	The study revealed that while general awareness of MERS-CoV was moderate, significant gaps existed in knowledge about the disease's incubation period,

				using a well-designed multistage questionnaire.	clinical picture and epidemiology. Age, education and occupation were significant predictors of awareness levels, with the Ministry of Health identified as the primary information source.

4. Discussion

4.1 Saudi Arabia's Response to Global Pandemics: Healthcare System Reforms

Saudi Arabia's response to the COVID-19 pandemic was characterized by prompt and decisive government actions and public health measures to control the virus's spread. Even before the first confirmed case, authorities conducted risk assessments for mass gatherings, leading to the suspension of the Umrah pilgrimage on February 27, 2020. In recognition of the dangers posed by crowded worship spaces, approximately 80,000 mosques were temporarily closed by the Saudi Council of Senior Scholars, including the Two Holy Mosques in Makkah and Medina, with daily and Friday prayers suspended starting March 17, 2020. Rigorous social distancing measures were enforced, including the suspension of all domestic public transport by March 20, 2020 and the implementation of a partial curfew from March 23, 2020. Schools and universities were closed on March 8 by the Ministry of Education with a shift to online education to reduce transmission in congregated settings. The combination of proactive risk assessments, rapid policy implementation and effective communication probably reduced transmission risks and supported public compliance, aiming to minimizing the epidemic curve (Yezli & Khan, 2020).

The study of Saudi Arabia's response to the COVID-19 pandemic examined the government's implementation of various public health measures, including border closures, regional lockdowns and restricted curfew hours to suppress virus transmission. Utilizing the Autoregressive Integrated Moving Average (ARIMA) model, the research analyzed daily number of confirmed COVID-19 cases based on data obtained from the Saudi Ministry of Health for the period from March 2 to April 20, 2020. The findings suggested that despite the implemented measures, the projections continued to rise in cases, potentially reaching 7,668 new infections by May 21, 2020. The study emphasized on the importance of community engagement and proactive health monitoring, recommending regular health checks at local clinics and isolation of high transmission areas to better control outbreaks (Alzahrani et al., 2020).

A cross-sectional study, involving 103 employees from the medical supply chain across various healthcare sectors, found that approximately 51% of respondents experienced shortages of ten or more essential medications, with specific drugs such as tocilizumab and hydroxychloroquine being particularly affected. Additionally, while around 70% of participants reported no significant change in prescription drug prices, 53% noted a price increase of at least 25% for PPE. These results highlight the financial pressure on healthcare systems from increased public spending and emphasize the need for better resource management and enhanced local manufacturing to address shortages and minimize economic impacts. The study recommends improved communication between public and private health sectors to prevent future supply issues (Aljadeed et al., 2021).

The new Model of Care (MOC) in Saudi Arabia aims to reform the healthcare system by transitioning from an activity-based to an outcome-based payment model, which promotes superior performance and quality of care. This model emphasizes long-term management of healthcare costs and the encouragement of healthier lifestyles through enhanced collaboration among providers and the establishment of Accountable Care Organizations (ACOs). The study employed a comprehensive analysis of the MOC's implementation, focusing on six care systems addressing various health needs

such as chronic conditions, urgent problems and preventive care and forty-two interventions. The findings indicate that the MOC significantly improves clinical effectiveness, patient experiences, ensures sustainability and financial transparency, aligning with the Kingdom's Vision 2030 objectives (Chowdhury et al., 2021).

4.2 Technological Integration and Public Health Strategies in Saudi Arabia

During the COVID-19 pandemic in Saudi Arabia, sustainable health strategies included vaccination campaigns, quarantine, lockdowns and social distancing measures. The Saudi Ministry of Health (MOH) led extensive vaccination efforts, employing applications such as Tawakkalna and Sehaty for vaccine access and medical consultations without physical interactions. Early implementation of quarantine and lockdown measures, including suspension of international flights and mass gatherings, was essential in preventing case importation. The evolving response incorporated flexible measures such as social distancing and technology for contact tracing. A mixed-methods analysis demonstrated that these early, decisive actions significantly reduced confirmed COVID-19 cases. The findings suggested that vaccination campaigns and preventive strategies effectively reduced virus spread and contributes to a notable decrease in infections by late August 2021, thereby establishing a foundation for future public health responses (Amamou & Ben-Ahmed, 2023).

The study conducted by Kaliyadan et al employing a cross-sectional design with an electronic survey to evaluate telemedicine and remote care during the COVID-19 pandemic in Saudi Arabia. The survey, which included demographic data and a Likert scale to assess physicians' attitudes towards telemedicine and perceived barriers, revealed that a substantial majority of respondents (87.5%) acknowledged that telemedicine could decrease unnecessary outpatient visits. Furthermore, 89.5% believed its efficacy varied by specialty. Approximately 58.1% of physicians reported utilizing telemedicine during the pandemic, with WhatsApp being the most frequently used platform (53.8%). However, significant barriers were identified, including technological limitations (66.6%) and concerns about diagnostic reliability (66.1%), emphasizing on the necessity for enhanced development and support to improve telemedicine integration into the healthcare system (Kaliyadan et al., 2020).

During the COVID-19 pandemic, Saudi Arabia integrated telemedicine into its healthcare system in order to maintain continuity of care while reducing in-person visits. A thorough review of publicly available data, including official announcements and peer-reviewed literature from March 20 to June 20, 2020, documented these adaptations. The findings indicated that the MOH activated teleconsultation applications, enabling institutions such as King Saud Medical City and Dr. Sulaiman Al Habib Medical Group to provide remote patient services. A royal decree from King Salman bin Abdulaziz Al Saud supported the use of telemedicine for diagnostic and management purposes both at home and in workplaces. The MOH also established the Call (937) Service Center for COVID-19 inquiries and employed WhatsApp for patient communication regarding medication refills and follow-ups. Additionally, innovative solutions, including robotic monitoring systems in intensive care units, were introduced, with around 19 digital applications and platforms launched to enhance public health functions, highlighting a significant shift towards technology integration in healthcare delivery (Hassounah et al., 2020).

The study emphasizes on the significant role of media and technology in public health education and awareness, specifically concerning Middle East Respiratory Syndrome-related Coronavirus (MERS-CoV). The research conducted in Al-Jouf, Saudi Arabia, employed a voluntary, personal interview survey to assess public knowledge and information sources about MERS-CoV. Findings revealed that the MOH, social networks and community communication were the

most effective information sources, with effectiveness rates of 25%, 23.7%, and 22.6%, respectively. Despite generally high awareness levels among younger and more educated respondents, significant gaps persisted in understanding transmission methods, incubation periods and global epidemiological contexts. The study highlights the effectiveness of media campaigns and social media in information transmission and emphasizes the need for expanding public health education initiatives and employing technological tools to enhance awareness and control of disease outbreaks (Nooh et al., 2021).

4.3 Role of AI in Pandemic Management: Enhancing Digital Health, Telemedicine and Vaccine Development

The study conducted by Polley et al., in which advanced technologies such as AI enhance the functionality of Digital Immunity Passports. By associating biometric identifiers with health records, it facilitates accurate and secure verification of individuals' COVID-19 statuses (testing, recovery, and vaccination) which is essential for pandemic management. The framework employs industry standards such as OAuth2/OIDC and FIDO2/WebAuthN for secure authentication and adheres to global privacy regulations. AI optimizes system scalability and reliability, enabling real-time verification and decision-making, which enhances both security and user experience. This approach improves pandemic response efficiency and provides a commercially viable, globally adaptable solution for future health emergencies (Polley et al., 2021).

Digital health records, including National Health Information Databases (NHIDs), are essential for real-time updates and monitoring in pandemic management. AI enhances the continuous updating and analysis of health data, enabling the tracking of disease spread, identification of hotspots and monitoring of individual health statuses. Real-time data facilitates prompt decision-making and timely interventions by health authorities. AI algorithms also improve the accuracy of health record matching, minimizing errors such as misidentifications, which are important during pandemics. The approach, demonstrated by countries such as Denmark, involves a phased implementation of AI systems and regulations, focusing initially on security and progressively expanding data sensitivity, thereby improving public health outcomes through accurate data, effective resource allocation and enhanced disease prevention strategies (Beck et al., 2018).

The study by Alamri et al., in 2022 integrates telemedicine in order to modernize healthcare. The study utilized both quantitative surveys and qualitative focus group discussions to assess healthcare professionals' views on teleclinics. The results indicate that perceived usefulness (PU) and perceived ease of use (PEU) significantly impact behavioral intention (BI) towards telemedicine emphasizing its role in improving healthcare efficiency. These findings support Vision 2030's objective of technological advancement in healthcare. They highlight the necessity for ongoing investment in technological infrastructure, training and system integration to fulfill the strategic goals of a modernized healthcare system (Alamri et al., 2022).

AI has significantly facilitated vaccine development and drug discovery for COVID-19 through the application of deep learning (DL), machine learning (ML) and artificial neural networks (ANN). In vaccine development, AI has advanced the design of epitope-based vaccines by predicting antigenic sites and optimizing vaccine candidates, exemplified by (Sarkar et al., 2020), who employed immune-informatics and molecular docking and (Russo et al., 2022), who developed an in silico pipeline to forecast cross-reactive immunity against variants such as Omicron. In drug discovery, AI models, including deep Q-learning networks by (Tang et al., 2022) and generative networks by (Gao et al., 2020), have been significant in identifying novel compounds and drug repurposing opportunities. Additionally, AI's role in predicting drug-

target interactions, as demonstrated by (Beck et al., 2020) and network-based algorithms by (Ge et al., 2020) in identifying inhibitors such as CVL218, emphasizes on its transformative impact. Nonetheless, challenges such as data quality, result validation across diverse populations and ethical considerations remain essential for enhancing AI's effectiveness in vaccine and drug development (Bagabir et al., 2022).

4.4 AI-Driven Innovations in Pandemic Management: Case Studies from Saudi Arabia

The study by Khan et al., emphasizes on the significant role of AI and digital technologies in managing the COVID-19 pandemic in Saudi Arabia. The Tawakkalna application was significant in controlling virus spread by tracking infected individuals, enforcing social distancing and restricting access to large gatherings. It utilized digital profiles to provide personalized information on infection status, vaccination history and exposure risks, thereby reducing contact between infected and uninfected individuals. The application's success in Al Madinah Al Mounawarah, where it effectively reduced virus transmission and managed public health, highlights the value of integrating digital solutions into public health strategies. Nonetheless, the study request for more extensive research to assess the broader and long-term impacts of such technologies in various cities (Khan et al., 2021).

The study highlights the important role of AI and technological tools in pandemic management, exemplified by their use during the COVID-19 outbreak. Early in the crisis, Saudi Arabia implemented digital solutions, including a real-time interactive map and an AI-enabled chatbot by the National Health Information Center, to provide updates and guidance on COVID-19. AI technologies were also employed in Taiwan to enhance national databases and integrate them with immigration systems for efficient traveler tracking and risk assessment of travelers. In the U.S. and Singapore, telehealth and chatbots facilitated remote care and information distribution. In Saudi Arabia, digital tools such as the COVID-19 Dashboard and multiple mobile apps were necessary for risk communication and public health management. While these digital tools proved effective in delivering timely information and supporting public health management, challenges related to interoperability and privacy management were noted, emphasizing on the requirement for ongoing development of digital solutions for future pandemics (Hassounah et al., 2020).

The research access the efficacy of various computational models in predicting and managing pandemic outbreaks in Saudia Arabia. The proposed framework, which combines the Fuzzy Analytic Hierarchy Process (Fuzzy AHP) with dynamic modeling, was tested against seven alternative models: The Reservoir People Transmission Network Model, Time Series Model, Spreading Rate of the Disease Model, Susceptible-Infected-Recovered Model, Dynamic Model, Multi-Modelling Approach Model and Susceptible-Exposed-Infectious-Recovered Model. The Fuzzy AHP methodology was utilized to evaluate the models by synthesizing fuzzy pairwise comparison matrices and computing defuzzified values and consistency ratios. The findings revealed that the proposed model (M8) achieved the highest effectiveness with a weight of 0.25650 and a consistency ratio of 0.0333, surpassing the other models in controlling COVID-19 transmission. Additionally, this model exhibited superior performance in terms of societal impact, prediction of infection dynamics and economic implications in Saudi Arabia, highlighting the fundamental aspect of AI-driven frameworks in effective and timely pandemic management (Baz et al., 2020).

Innovations such as AI, the Internet of Things (IoT), drones and 5G technology have significantly contributed to reducing the pandemic's effects. AI and machine learning algorithms have been employed to analyze extensive datasets, forecast outbreak trends and aid in the development of vaccines and treatments. IoT devices have enabled remote patient monitoring and management, while drones and 5G-enabled robots have improved sanitation, facilitated medicine

delivery and supported telemedicine through high-speed data transmission and low-latency communication. Collectively, these technologies enhance real-time monitoring, automate epidemic control measures and optimize healthcare delivery, emphasizing on their transformative impact on managing global health crises and advancing smart city infrastructure (Chamola et al., 2020).

4.5 SEIQR Epidemic Model

Mathematical models are useful in understanding the path of infection when it enters a community and determining whether it will be eradicated or persist. During the pandemic, the coronavirus (COVID-19) has caused concern among researchers, governments, and the general public due to its rapid spread and high death toll. The field of mathematical epidemiology was first defined in 1927 by Kermack and McKendrick as an SIR model. Nesteruk also developed the variables by using the proposed model for presenting a SIR epidemiological model and explaining how to control the spread of the disease. However, to restore the epidemic with the inclusion of social distancing and lockdown, computer technology has helped facilitate the calculation of matrices using logarithms to determine the spread of infection from the context of medical engineering that emerged in 1972 to determine the dynamics of infection transmission and estimate the national and global spread of the infectious disease. A modified SIR (susceptible, infected, and recovered) epidemic model was introduced to discover the confirmed number of infected cases in isolation wards and intensive care units. Youssef et al presented an epidemiological model with a new way to assess and manage the COVID-19 pandemic in Saudi Arabia. Actual COVID-19 data were used and the results showed that the susceptible class (S), exposed class (E), infected class (I), quarantined class (Q), and recovered class (R) [SEIQR] model is useful for studying the spread of epidemics in Saudi Arabia and other countries. The model provided new and different reproduction numbers accurate and sensitive to the modified SEIQR model. Five steps were considered the ideal action to implement comprehensive advice to help the population of Saudi Arabia slow the spread of the Coronavirus (COVID-19). Prevention was one of the main goals of this action instead of treatment by staying at home and keeping patients in an isolated area or protected place (Youssef et al, 2021).

5. Conclusion

In conclusion, Saudi Arabia's experience with recurrent viral outbreaks emphasizes on the necessity for strong, adaptive public health strategies customized to its unique socio-religious context. The nation's successful management of H1N1, MERS-CoV and COVID-19 through strict measures highlights the importance of continuous improvement in crisis management. Integrating advanced technologies, especially AI, has proven significant in enhancing diagnostic accuracy, optimizing resource distribution and improving overall health outcomes. As Saudi Arabia continues to host millions of pilgrims, adopting AI-driven solutions and developing resilient health systems will be essential for future pandemic preparedness and global health security.

6. Limitation and Future Implications

The review does not fully address the implementation challenges of AI-driven solutions and their long-term effectiveness in pandemic management. Additionally, while the review highlights advanced technologies, it lacks a comprehensive analysis of their potential ethical and data privacy issues. Future efforts should focus on enhancing predictive analytics, optimizing resource management and improving outbreak preparedness through technology. Strengthening these capabilities will not only strengthen Saudi Arabia's resilience to global health emergencies but also provide a model for

other nations, demonstrating the potential of integrated, technology-supported health systems to manage pandemics effectively. Moreover, strengthening international collaboration and utilizing real-time data analytics will be essential in mitigating the impact of future outbreaks. Moreover, integrating advanced technologies such as AI with traditional public health measures will be essential for developing more strong and responsive health systems.

References

- Abdo, K. W. (2024). The Role of Artificial Intelligence in Improving Healthcare Operations in Saudi Arabia: Analytical Study of Current and Future Systems. Nanotechnology Perceptions, 743–758-743–758.
- Alammash, S. A., Guo, P. S., & Vinnikova, A. (2021). Saudi Arabia and the Heart of Islam in Vision 2030: Impact on International Relations. Arab. J. Sci. Publ.(AJSP), 2663, 5798.
- Alamri, A. F., Alomari, F. K., Danash, A. M., Aljoudi, M. T., Almasharqa, A. I., Almasloot, A. M., Alwhaibi, R. M., Hasan, M. M., & Zaidi, U. (2022). Perception of healthcare providers during the COVID-19 pandemic: a mixed method survey in an integrated healthcare delivery system in Saudi Arabia. International journal of environmental research and public health, 19(24), 16676.
- AlFattani, A., AlMeharish, A., Nasim, M., AlQahtani, K., & AlMudraa, S. (2021). Ten public health strategies to control the Covid-19 pandemic: The Saudi Experience. IJID regions, 1, 12-19.
- Alhazmi, A. M., Alshammari, S. A., Alenazi, H. A., Shaik, S. A., AlZaid, H. M., Almahmoud, N. S., & Alshammari, H. S. (2019). Community's compliance with measures for the prevention of respiratory infections in Riyadh, Saudi Arabia. Journal of Family and Community Medicine, 26(3), 173-180.
- Aljadeed, R., AlRuthia, Y., Balkhi, B., Sales, I., Alwhaibi, M., Almohammed, O., Alotaibi, A. J., Alrumaih, A. M., & Asiri, Y. (2021). The impact of COVID-19 on essential medicines and personal protective equipment availability and prices in Saudi Arabia. Healthcare,
- Alzahrani, S. I., Aljamaan, I. A., & Al-Fakih, E. A. (2020). Forecasting the spread of the COVID-19 pandemic in Saudi Arabia using ARIMA prediction model under current public health interventions. Journal of infection and public health, 13(7), 914-919.
- Amamou, M., & Ben-Ahmed, K. (2023). Managing the COVID-19 pandemic in thirty-two policy measures in Saudi Arabia: a mixed-methods analysis. Journal of infection and public health, 16(10), 1650-1658.
- Bagabir, S. A., Ibrahim, N. K., Bagabir, H. A., & Ateeq, R. H. (2022). Covid-19 and Artificial Intelligence: Genome sequencing, drug development and vaccine discovery. Journal of infection and public health, 15(2), 289-296.
- Baz, A., Alhakami, H., & Alshareef, E. (2020). A Framework of Computational Model for Predicting the Spread of COVID-19 Pandemic in Saudi Arabia. International Journal of Intelligent Engineering & Systems, 13(5).
- Beck, B. R., Shin, B., Choi, Y., Park, S., & Kang, K. (2020). Predicting commercially available antiviral drugs that may act on the novel coronavirus (SARS-CoV-2) through a drug-target interaction deep learning model. Computational and structural biotechnology journal, 18, 784-790.
- Beck, E. J., Shields, J. M., Tanna, G., Henning, G., De Vega, I., Andrews, G., Boucher, P., Benting, L., Garcia-Calleja, J. M., & Cutler, J. (2018). Developing and implementing national health identifiers in resource limited countries: why, what, who, when and how? Global health action, 11(1), 1440782.
- Chamola, V., Hassija, V., Gupta, V., & Guizani, M. (2020). A comprehensive review of the COVID-19 pandemic and the role of IoT, drones, AI, blockchain, and 5G in managing its impact. Ieee access, 8, 90225-90265.
- Chiu, K. H.-Y., Sridhar, S., & Yuen, K.-Y. (2023). Preparation for the next pandemic: challenges in strengthening surveillance. Emerging Microbes & Infections, 12(2), 2240441.
- Chowdhury, S., Mok, D., & Leenen, L. (2021). Transformation of health care and the new model of care in Saudi Arabia: Kingdom's Vision 2030. Journal of Medicine and Life, 14(3), 347.
- Elkhatib, W. F., Abdelkareem, S. S., Khalaf, W. S., Shahin, M. I., Elfadil, D., Alhazmi, A., El-Batal, A. I., & El-Sayyad, G. S. (2022). Narrative review on century of respiratory pandemics from Spanish flu to COVID-19 and impact of nanotechnology on COVID-19 diagnosis and immune system boosting. Virology journal, 19(1), 167.
- Gao, K., Nguyen, D. D., Wang, R., & Wei, G.-W. (2020). Machine intelligence design of 2019-nCoV drugs. BioRxiv.

- Ge, Y., Tian, T., Huang, S., Wan, F., Li, J., Li, S., Yang, H., Hong, L., Wu, N., & Yuan, E. (2020). A data-driven drug repositioning framework discovered a potential therapeutic agent targeting COVID-19. BioRxiv, 2020.2003. 2011.986836.
- Gössling, S., Scott, D., & Hall, C. M. (2020). Pandemics, tourism and global change: a rapid assessment of COVID-19. Journal of sustainable tourism, 29(1), 1-20.
- Hassounah, M., Raheel, H., & Alhefzi, M. (2020). Digital response during the COVID-19 pandemic in Saudi Arabia. Journal of medical Internet research, 22(9), e19338.
- Kaliyadan, F., Al Ameer, M. A., Al Ameer, A., & Al Alwan, Q. (2020). Telemedicine practice in Saudi Arabia during the COVID-19 pandemic. Cureus, 12(12).
- Khan, A., Alahmari, A., Almuzaini, Y., Alturki, N., Aburas, A., Alamri, F. A., Albagami, M., Alzaid, M., Alharbi, T., & Alomar, R. (2021). The role of digital technology in responding to COVID-19 pandemic: Saudi Arabia's experience. Risk Management and Healthcare Policy, 3923-3934.
- Kontis, V., Bennett, J. E., Rashid, T., Parks, R. M., Pearson-Stuttard, J., Guillot, M., Asaria, P., Zhou, B., Battaglini, M., & Corsetti, G. (2020). Magnitude, demographics and dynamics of the effect of the first wave of the COVID-19 pandemic on all-cause mortality in 21 industrialized countries. Nature medicine, 26(12), 1919-1928.
- Memish, Z. A., Perlman, S., Van Kerkhove, M. D., & Zumla, A. (2020). Middle East respiratory syndrome. The Lancet, 395(10229), 1063-1077.
- Nooh, H. Z., Alshammary, R. H., Alenezy, J. M., Alrowaili, N. H., Alsharari, A. J., Alenzi, N. M., & Sabaa, H. E. (2021). Public awareness of coronavirus in Al-Jouf region, Saudi Arabia. Journal of Public Health, 29, 1107-1114.
- Polley, J. C., Politis, I., Xenakis, C., Master, A., & Kępkowski, M. (2021). On an innovative architecture for digital immunity passports and vaccination certificates. arXiv preprint arXiv:2103.04142.
- Russo, G., Di Salvatore, V., Sgroi, G., Parasiliti Palumbo, G. A., Reche, P. A., & Pappalardo, F. (2022). A multi-step and multi-scale bioinformatic protocol to investigate potential SARS-CoV-2 vaccine targets. Briefings in bioinformatics, 23(1), bbab403.
- Sarkar, B., Ullah, M. A., Johora, F. T., Taniya, M. A., & Araf, Y. (2020). The essential facts of Wuhan novel coronavirus outbreak in China and epitope-based vaccine designing against 2019-nCoV. BioRxiv, 2020.2002. 2005.935072.
- Syrowatka, A., Kuznetsova, M., Alsubai, A., Beckman, A. L., Bain, P. A., Craig, K. J. T., Hu, J., Jackson, G. P., Rhee, K., & Bates, D. W. (2021). Leveraging artificial intelligence for pandemic preparedness and response: a scoping review to identify key use cases. NPJ digital medicine, 4(1), 96.
- Tang, B., He, F., Liu, D., He, F., Wu, T., Fang, M., Niu, Z., Wu, Z., & Xu, D. (2022). AI-aided design of novel targeted covalent inhibitors against SARS-CoV-2. Biomolecules, 12(6), 746.
- Wilder-Smith, A., & Freedman, D. O. (2020). Isolation, quarantine, social distancing and community containment: pivotal role for old-style public health measures in the novel coronavirus (2019-nCoV) outbreak. Journal of travel medicine, 27(2), taaa020.
- Yezli, S., & Khan, A. (2020). COVID-19 social distancing in the Kingdom of Saudi Arabia: Bold measures in the face of political, economic, social and religious challenges. Travel medicine and infectious disease, 37, 101692.
- Youssef, H., Alghamdi, N., Ezzat, M.A., El-Bary, A.A. and Shawky, A.M.(2021). Study on the SEIQR model and applying the epidemiological rates of COVID-19 epidemic spread in Saudi Arabia. Infectious Disease Modelling, 6, pp.678-692.
- Youssef, H.M., Alghamdi, N.A., Ezzat, M.A., El-Bary, A.A. and Shawky, A.M., (2020). A modified SEIR model applied to the data of COVID-19 spread in Saudi Arabia. AIP advances, 10(12).
- Youssef, H.M., Alghamdi, N.A., Ezzat, M.A., El-Bary, A.A. and Shawky, A.M., 2020. A new dynamical modeling SEIR with global analysis applied to the real data of spreading COVID-19 in Saudi Arabia. Math. Biosci. Eng, 17(6), pp.7018-7044.
- Youssef, H.M., Alghamdi, N., Ezzat, M.A., El-Bary, A.A. and Shawky, A.M., 2022. A proposed modified SEIQR epidemic model to analyze the COVID-19 spreading in Saudi Arabia. Alexandria Engineering Journal, 61(3), pp.2456-2470.

Theme of Modern Systems and Technologies in Transportation and Mass Gatherings Management

A Cloud-based Route Planning Framework for Hajj

Thamir M. Qadah*, Emad Felemban

Department of Computer and Network Engineering, Umm Al-Qura University

*Corresponding author: E-mail (tmqadah@uqu.edu.sa)

إطار عمل لتخطيط عمليات النقل للحج باستخدام الحوسبة السحابية

ثامر محمد قدح*، عماد فلمبان

قسم هندسة الحاسب والشبكات - جامعة أم القرى

Abstract

Careful transportation planning during Hajj is crucial to help millions of people perform their pilgrimage conveniently. To help realize the Pilgrimage Experience Program (PEP) objectives of reaching 30 million pilgrims, robust and effective intelligent transportation planning frameworks are needed. In this paper, we propose a cloud-based route-planning framework that can be used in the mobility planning phase of Hajj. Our framework can help transportation planning authorities to carefully analyze transportation plans and study alternatives in preparation for the Hajj season. We examined three different approaches to identify and analyze transportation routes from Makkah to Mina. Moreover, we discuss the advantages and disadvantages of the proposed three approaches. We also discussed the major research and development challenges of route planning cloud-based tools for intelligent transportation in Hajj. This paper demonstrates the utilization of cloud computing and geospatial data analysis tools for route planning for Hajj.

Keywords: Cloud Computing, Geospatial Data Analysis, Hajj transportation planning, routing web services

1. Introduction

The Hajj pilgrimage is one of the largest annual religious gatherings globally, drawing millions of Muslims to the holy cities of Makkah and Madina in Saudi Arabia. The sheer scale of the event presents significant logistical challenges, particularly in transportation planning. Efficient movement of pilgrims between the Holy sites is essential to ensure safety, convenience, and fulfillment of religious obligations. The Pilgrimage Experience Program (PEP) aims to increase the number of pilgrims to 30 million, intensifying the need for robust transportation solutions. Traditional transportation planning methods may need to be revised to handle the complexities associated with such massive crowds . Furthermore, cloud technologies and services have become more pervasive and mature. Cloud-based technologies and services help scale out the resources required for Hajj planning, making it imperative to utilize them. Moreover, the landscape for data analysis tools has matured significantly, and there is negligible adoption in the contexts of planning and operations in Hajj. This paper proposes a cloud-based route-planning framework designed to aid transportation authorities during the Hajj mobility planning phase. By leveraging cloud computing and advanced data analytics, the framework facilitates the analysis of transportation plans and the exploration of alternative routes. We investigate three approaches for identifying and analyzing transportation routes from Makkah to Mina, discussing their advantages and disadvantages. Additionally,

we address the primary research and development challenges in deploying cloud-based route planning tools for intelligent transportation during Hajj.

2. Routes Planning in Hajj

The fundamental problem we have addressed in this paper can be described as follows. Informally, given the locations of residences of Hajj groups and a set of locations of entrances to the Holy Sites, how can we plan and analyze possible routes? This is a crucial problem for planning transportation to ensure the safety and successful operations during Hajj. Furthermore, we want to understand how different tools may produce different results . To address the problems above, we developed a framework that utilizes cloud-based services and open-source software tools. We started by providing an overview of the proposed framework .

2.1 .Framework Overview

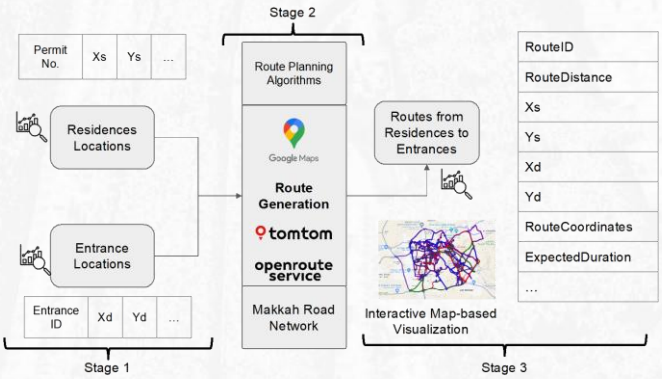


Figure 1 Route generation and planning framework

Figure 1 illustrates a high-level overview of the proposed framework, which consists of three stages. In stage 1, our proposed framework takes two data sets as input. The first set is the residence locations of Hajj groups. The most crucial information in this dataset is the location of the residence that we donate as (Xs, Ys) for each residence. The data usually contain an identifier for each registered residence, such as the permit number. Other information can also exist in the dataset, such as the name of the company that provides the Hajj service and the nationality of pilgrims in the group. While the latter pieces of information are irrelevant to the route generation process, they are still propagated through the framework's process to facilitate better data analysis. The second data set used as an input to our framework is the entrance locations to the Holy sites. These locations are usually determined to ensure controlled access to the Holy sites such as Mina and Arafat. For each entrance, the location coordinates are provided and are denoted as (Xd, Yd). Each entrance has an identifier (Entrance ID) to help identify each entrance location uniquely. Similar to the first data set, additional information may be provided for each entrance. Our framework allows geospatial data analysis and visualization operations on both datasets at this stage. We discuss tools that facilitate such analysis in the next section .

The second stage is where the actual routes are generated. Let us denote the first dataset as L and the second dataset as E. Finding routes can be abstracted as R = find_routes (L, E, M, O), where M denotes the map-based data of Makkah, including the road network data. O denotes options to control route generation. The find_route procedure utilizes state-of-the-art routing-planning algorithms and finds routes constrained by M and O. In other words, the routes in R must be valid in M and comply with options in O .

The output of the route-planning stage can be analyzed and visualized interactively using geospatial data analysis tools in Stage 3. For example, one of the tools (i.e., Geopandas) allows for generating an interactive web UI to visualize the routes. It includes typical map-based UI interactions such as pan and zoom interactions. The output is a set of paths with different additional attributes (e.g., RouteDistance, RouteCoordinates, ExpectedDuration). For instance, by specifying the option to generate multiple routes in O, the output will contain multiple routes between every source and destination. One of them is designated as the primary route (e.g., the route with the shortest length), while others are designated as alternatives. In the next section, we give an overview of the software tools used by our proposed framework.

2.2 Software Tools Overview

In this section, we discussed the software tools that are used to implement our framework. The tools were divided into two categories: Geospatial Data Management and Analysis and Routing Libraries.

2.2.1 Geospatial Data Management and Analysis

Geospatial data analysis tools include Pandas (*Pandas - Python Data Analysis Library*, 2024) and GeoPandas (*GeoPandas v1.0.1*, 2024). Pandas is an open-source Python library that offers high-performance data manipulation and analysis tools. Its Data Frame and series objects are central to Pandas, which provide efficient structures for storing and operating on tabular and time-series data. With Pandas, users can perform a wide range of tasks, such as data cleaning, aggregation, and transformation. It supports data operations like merging, reshaping, selecting subsets, handling missing data, and performing statistical analysis.

GeoPandas builds upon the foundations of Pandas to enable the handling of geospatial data. By extending the DataFrame object to include geographic information, GeoPandas allows for manipulating spatial data types such as points, lines, and polygons. It integrates seamlessly with libraries like Shapely for geometric operations and Matplotlib for plotting. Users can perform spatial queries, conduct geometric manipulations, and visualize geographic data efficiently. GeoPandas simplifies complex spatial analyses within the familiar Pandas framework.

2.2.2 .Routing Libraries

Our framework supports route generation via routing web services, which can be utilized using their respective programming libraries or HTTP RESTful API. In the proposed framework, we experimented with three notable routing libraries. These three are the Google Routes API (GR), TomTom Routing API (TTR), and OpenRouteService (ORS).

The GR API is a comprehensive service that enables developers to calculate optimal routes between locations while considering real-time traffic conditions, road incidents, and user preferences (Google, 2024). It supports multiple modes of transportation, including driving, walking, bicycling, and public transit. Key relevant features include turn-by-turn navigation, distance and duration estimates, and optimizing routes with multiple waypoints. The API also allows for customization, such as avoiding toll roads or highways, and integrates seamlessly with other Google Maps Platform services, enhancing its utility in diverse applications.

TomTom Routing API (TTR) provides high-quality routing services backed by accurate map data and live traffic information (*TomTom Routing APIs*, 2024). It offers various routing types, like the fastest, shortest, and most economical routes, considering real-time traffic congestion and historical traffic patterns. Advanced functionalities include batch routing for processing multiple routes simultaneously and matrix routing to efficiently calculate travel times and distances between many origins and destinations .

Both of the above routing services are commercial cloud-based services, and users are charged per request. An open-source alternative is ORS (*Open Routes Service*, 2024). Using ORS, users can avoid paying per request and request quotas and limits imposed by GR and TTR. ORS is an open-source routing service based on OpenStreetMap data, offering flexibility and customization. With ORS, you can deploy your backend services and pay for the cloud infrastructure.

We conducted an experimental study to evaluate all three approaches above. In the next section, we presented our experimental study. Our evaluation is qualitative and preliminary, but we plan to perform a more comprehensive study in future work.

3. Route Planning API Study

In this section, we study the quality of the routing results obtained from the libraries above and the APIs.

3.1. Study Methodology

We design a simple experiment to study the selected libraries. We use Google Colab (Google Colab, 2024) as a platform to perform the study. The experiment follows our proposed framework. We implemented three versions of the find_routes procedure. The only difference in the versions is the backend API used to generate the routes. We set L = {(Xs, Ys)}, E = {(Xd, Yd)}. M is implicit with the routing API because the default road network is used for each API. O is the set of options, including finding the shortest path, using the car as the travel mode, and ignoring traffic for all cases.

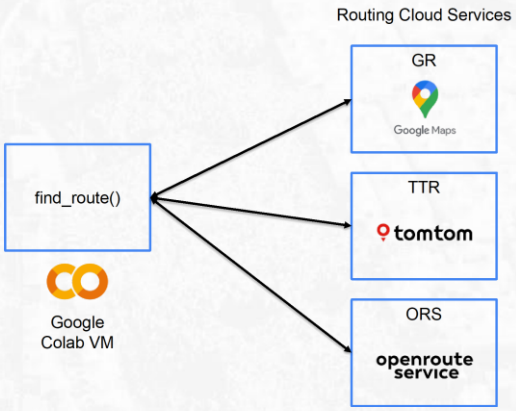


Figure 2 Cloud-based Experimental Settings

Figure 2 illustrates the cloud-based deployment of our experimental environment. Our implementations of the find_route procedure run on Google Colab's virtual machine (VM) supported by Google's Cloud. The VM is connected to the internet. Therefore, it can request the different providers for the Routing API over HTTP. HTTP responses are received by the process running the find_route procedure. API keys are used for each provider-specific provider implementation implementation. We used GeoPanda's ability to create interactive visualization with the Colab notebook.

3.2 Results and Discussion

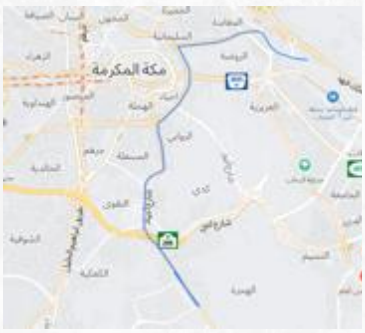


Figure 3 TTR API route results

Figure 4 GR API route results

Figure 5 ORS API route results

Table 4 Characteristics of Generated Routes

API	Distance (m)	Duration (s)
TTR	12395	944
GR	12331	1130
ORS	18679.3	1096.4

Figure 3, Figure 4, and Figure 5 show a screenshot of the map-based visualization for the routes obtained by TTR, GR, and ORS. We used the map tiles that belong to each service. Commercial APIs (i.e., GR and TTR) show better route results than the open-source ones (i.e., ORS). The routing algorithms and the quality road network dataset are the main reasons for this. ORS uses OpenStreetMap data (OpenStreetMap, 2024) , while GR and TTR rely on professionally maintained datasets. Notice that the route obtained from ORS is longer than from GR and TTR.

More concrete route characteristics are shown in Table 4 While the route visualization shows almost identical routes obtained from GR and TTR, the distance and duration estimations are different, probably due to differences in their implementations. ORS seems to show a lower duration than GR despite the longer distance. However, ORS's route uses a freeway with higher speed limits. Thus, the estimation for the duration is lower.

3.3 Discussion

While obtaining routes from cloud providers is straightforward, the accuracy of the results cannot be controlled unless the route generation is done using updated map data. During Hajj, the road network in Makkah typically changes to accommodate transportation plans. Thus, there is a need to have a way to perform route planning under the realistic conditions of Hajj. A nice feature of such APIs is that they allow users to specify the road network conditions and traffic traces. This requirement is novel for cloud providers.

The alternative solution is for the Hajj authorities to have their private virtual infrastructure for route planning, allowing complete data control. This approach also requires a data integration framework with all the entities involved in the Hajj operation. Another approach is to build simulated environments to help find better routing for realistic conditions.

4. Case Study: Planning and Analyzing Routes Makkah to Mina

This section reviews a case study on the route-generation process for planning transportation routes from the Hajj group's residence locations in Makkah to Mina. The main goal of this case study is to understand the intensity of a predetermined set of road usage during the official transportation period in Hajj.

We used the proposed framework to help with this task. Let us denote the predetermined set of roads as T, which is visualized in Figure 6. We also visualized the L and E in Figure 7 and Figure 8, respectively. We used GR as the backend for the find_route procedures for this task. The set of options O includes an additional constraint that requires generating one primary route and two alternative routes.

Figure 6 Predetermined set of Roads for the Case Study. We must answer the following question: How much are these road segments used?

Figure 7 Interactive visualization of the entrances of Mina, E

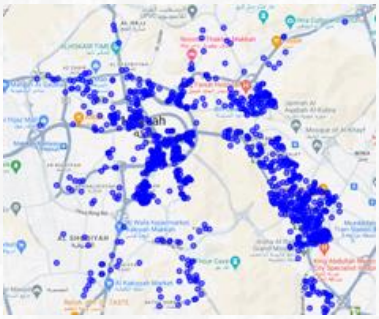


Figure 8 - Interactive visualization of residence locations, L

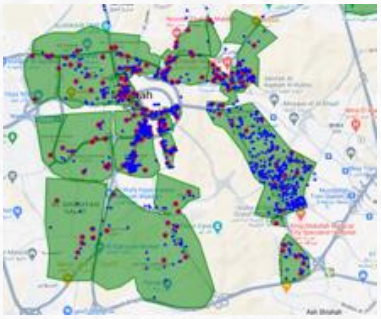


Figure 9 Interactive visualization for the spatially-aware sampling of residence locations

Simply generating routes at this point can be costly because the number of pairs can be huge. Because the road network infrastructure is fixed, many road segments are shared among routes. Thus, we can reduce the number of route generation requests by sampling. Unfortunately, naïve sampling may result in skewed samples concerning the spatial distribution of the residence locations. To solve this issue, we use spatially aware sampling, which ensures that the sampled locations are spread across the residential region. In Figure 9, an interactive visualization shows the samples. Blue circles are the residence locations. The red outline for the area indicates the selection as a part of the sampling procedure.

Figure 10 - Interactive visualization of generated routes. Green is the color of the primary routes. Red and blue routes are the alternatives.

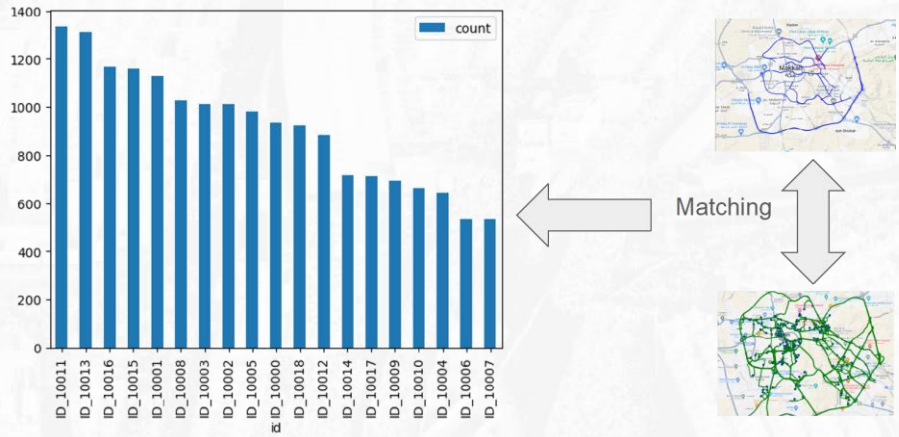


Figure 11 Computing densities of requested routes. On the left, we have the IDs for each route in T on the x-axis. We only consider the primary routes.

Now, we are ready to compute R according to the procedure find_route. Figure 10 shows all the routes generated after executing the find_route procedure, including the primary routes and their alternatives. To answer the question of the degree of utilization for the roads in T, we count the number of overlapping road segments among the generated road segments in R and T, as shown in Figure 11.

5. Related Work

In this section, we discussed our paper in relation to existing domains. Data science is an emerging field that can be used to solve fundamental problems in Hajj. (Stocker et al., 2024) Propose a conceptual framework for Mobility Data Science (MDS). Our work represents a step towards MDS because it focuses on mobility issues and challenges in Hajj.
(Shekhar et al., 2015) defines Spatial Computing (SC) as the field of computing that helps us create a new understanding of locations. Building tailored SC systems for Hajj that address the specific needs of its planning and operations using SC has become necessary. Our work scratches the surface of the required research in studying the application of SC to Hajj planning and operation. Another related field is the field of Route Recommendation (RR) (Zhang et al., 2024). (Zhang et al., 2024) surveys many methods and applications of RR. Hajj route planning is yet another application of RR that is not included in the survey. Furthermore, Hajj route planning also utilizes the surveyed methods, including classical ones or those based on deep learning (Zhang et al., 2024).

6. Conclusion and Future Work

In conclusion, the proposed cloud-based route-planning framework has the potential to significantly enhance the efficiency and effectiveness of transportation planning during Hajj. By leveraging cloud technologies and advanced data analytics, the framework enables transportation authorities to systematically analyze and optimize routes, ensuring millions of pilgrims' safe and smooth movement. By examining multiple routes from Makkah to Mina and addressing various operational challenges, this framework aims to improve logistical coordination and ultimately contribute to a more favorable pilgrimage experience. Future research should focus on refining the proposed methodologies, integrating real-time data, and exploring further advancements in cloud-based solutions. By embracing these innovations, Hajj authorities can better respond to the dynamic demands of Hajj, thus supporting the overarching goal of accommodating 30 million pilgrims while maintaining safety, convenience, and satisfaction during this significant religious journey.

7. Recommendations

Based on the outcomes of this research, we recommend the following:

1. The adoption of cloud-based tools for route planning and analysis for Hajj. This adoption ensures efficient and cost-effective planning.
2. The development and deployment of a cloud-based real-time geospatial data repository that integrates changes to road network and traffic updates from various data sources in the Hajj operational services. This data repository can be designed to ensure data privacy and integration, unlike using commercial cloud services such as (Google, 2024; TomTom Routing APIs, 2024) where data privacy is not guaranteed, and it is difficult to integrate with them beyond their public API.

References

- GeoPandas v1.0.1. (2024). https://geopandas.org/en/stable/
- Google. (2024). Google Maps Platform Documentation | Routes API | Google for Developers. https://developers.google.com/maps/documentation/routes
- Google Colab. (2024). Google Colab. Colab.Google. https://colab.google/
- Open Routes Service. (2024). Open Routes Service. https://openrouteservice.org/
- OpenStreetMap. (2024). OpenStreetMap. https://www.openstreetmap.org/about
- Pandas—Python Data Analysis Library. (2024). https://pandas.pydata.org/
- Shekhar, S., Feiner, S. K., & Aref, W. G. (2015). Spatial computing. Commun. ACM, 59(1), 72–81. https://doi.org/10.1145/2756547
- Stocker, A., Kaiser, C., Lechner, G., & Fellmann, M. (2024). A Conceptual Framework for Mobility Data Science. IEEE Access, 12, 117126–117142. IEEE Access. https://doi.org/10.1109/ACCESS.2024.3445166
- TomTom Routing APIs. (2024). TomTom. https://www.tomtom.com/products/routing-apis/
- Zhang, S., Luo, Z., Yang, L., Teng, F., & Li, T. (2024). A survey of route recommendations: Methods, applications, and opportunities. Information Fusion, 108, 102413. https://doi.org/10.1016/j.inffus.2024.102413

The Hajj Lab: A Multi-Layered Technological Approach to Enhancing Crowd Management through Stratospheric Airships and AI Analytics

Adnan A. Alshahrani

The Custodian of the Two Holy Mosques Institute for Hajj and Umrah Research, Umm Alqura University

*Corresponding author: E-mail (Ayshahrani@uqu.edu.sa)

مختبر الحج: نهج تقني متكامل لتعزيز إدارة الحشود باستخدام المناطيد الطبقية والتحليلات القائمة على الذكاء الاصطناعي

عدنان الشهراني

معهد خادم الحرمين الشريفين لأبحاث الحج والعمرة، جامعة أم القرى

Abstract

This study presents the development and potential of the Hajj Lab, an innovative platform designed to manage the complex crowd dynamics during the Hajj pilgrimage. Utilizing stratospheric airships, drones, on-site sensors, and AI-driven analytics, the Hajj Lab offers a real-time, multi-layered approach to crowd monitoring and management. The study employs an exploratory research methodology, reviewing existing literature and technologies to conceptualize the integration of these systems for real-time data collection and predictive analysis. By combining high-resolution 3D data with AI models, the platform allows for proactive interventions, improving safety and efficiency in managing millions of pilgrims. The findings demonstrate that the Hajj Lab addresses key challenges that traditional crowd management methods struggle with, such as overcrowding and bottlenecks, while also providing insights for long-term urban planning and infrastructure development. The study further explores the scalability of the Hajj Lab for use in other large-scale global events, setting a new standard for crowd management. The integration of these technologies offers significant implications for enhancing the overall safety and experience of large gatherings. Through continued innovation and interdisciplinary collaboration, the Hajj Lab has the potential to revolutionize future large-scale event management systems.

Keywords: Stratospheric Airships, Crowd Monitoring, Hajj Seasons, Artificial intelligence, Emergency Response, Environmental Analysis, Aerial Surveillance, Urban Studies.

1. Introduction

The Hajj, a cornerstone of Islamic faith, annually draws over 3 million pilgrims from diverse backgrounds, encompassing a wide range of ethnicities, ages, languages, and cultural traditions (Abalkhail & Al Amri, 2022; Haghani et al., 2023). This massive influx presents unique challenges, particularly in crowd management. Research highlight significant challenges faced by authorities in managing the vast number of pilgrims. The strict adherence to rituals often results in disasters, including overcrowding, individuals getting lost, medical emergencies, and congestion issues(Al-Wathinani et al., 2021).

To effectively address these problems, it is essential to obtain accurate and real-time crowd estimates at various sites, facilitating timely interventions. To ensure the safety and well-being of pilgrims, there's been a growing emphasis on employing advanced technologies to optimize crowd control and enhance the overall Hajj experience (E. Felemban et al., 2021; E. A. Felemban et al., 2020). These technological innovations are vital for mitigating risks, improving efficiency, and ultimately creating a more seamless pilgrimage for millions of participants each year.

The Kingdom of Saudi Arabia (KSA) has extensively studied crowd management, establishing specialized Institute dedicated to studying crowd behavior and crisis response under the name of the Custodian of the Two Holy Mosques Institute for Hajj and Umrah Research at Umm Al-Qura University. This institute conducts specialized research on challenges and crises faced by Hajj officials, offering numerous recommendations based on local expertise, studies, and experience. By integrating artificial intelligence (AI) and advanced technologies, such as 5G connectivity, KSA continues to enhance its crowd management strategies for large-scale events like Hajj (Abalkhail & Al Amri, 2022). These efforts have not only contributed to the successful management of Hajj seasons but have also positioned KSA as a global leader in crowd management (E. A. Felemban et al., 2020). With ongoing advancements and strategic implementations, the KSA is setting a global benchmark, ensuring the safety and well-being of millions of pilgrims annually.

The complexities of crowd management during Hajj present both challenges and opportunities, requiring innovative solutions and strategic coordination among authorities, local government, and technology providers (Abalkhail & Al Amri, 2022). Effective management frameworks must incorporate technological advancements while also adapting to dynamic conditions. Current literature emphasizes the importance of real-time systems capable of continuous monitoring and immediate data analysis to address congestion and safety risks. The Hajj Lab offers an integrated platform that combines traditional crowd management methods with advanced technologies. By leveraging urban planning, AI, and crisis management, this framework focuses on comprehensive data collection, analysis, and proactive risk mitigation. The cross-disciplinary approach equips the authorities to anticipate and mitigate risks associated with large crowds, particularly within the unique context of Hajj. By fostering collaboration and innovation, the Hajj Lab aims to improve safety and efficiency in managing the complex logistics of pilgrimage.

Within the Hajj Lab, technological components are synergistically integrated to create a holistic approach to crowd management. The stratospheric airships, equipped with multispectral sensors, are vital for wide-area surveillance, allowing for the capture of high-resolution 3D data. This data is not only invaluable in real-time for monitoring, but it is also instrumental for predictive analytics. Drones add a nuanced layer of surveillance, providing targeted data on specific areas of concern. Meanwhile, ground-based sensors contribute to critical environmental parameters, such as temperature and humidity, which can influence crowd behavior. The seamless integration of these technologies, coupled with advanced AI, enables Hajj officials to conduct quick analyses and implement strategic interventions to enhance crowd flow and reduce the likelihood of incidents (Abalkhail & Al Amri, 2022). This multifaceted approach creates an unprecedented level of insight and operational efficiency in managing the pilgrimage.

This paper aims to review current and emerging technologies, focusing on the capabilities of the Hajj Lab and the role of stratospheric airships in advancing crowd management strategies. The Hajj Lab, similar to the concept of an Urban Lab, is a dynamic platform designed to improve crowd management during Hajj by testing and refining real-time strategies. By integrating AI-driven analytics, drones, on-site sensors, and aerial surveillance from stratospheric airships, the Hajj Lab provides a comprehensive solution to monitor, predict, and manage crowd dynamics. This approach addresses risks such

as overcrowding and emergencies, enhancing decision-making processes and bolstering emergency response capabilities. Through this proactive model, Hajj management can transition to a more flexible and adaptive system, setting a new benchmark for managing large-scale events with greater safety and efficiency.

2. Literature Review

2.1. Overview of Crowd Management in Hajj: The complexities inherent in crowd management during the Hajj pilgrimage are exacerbated by the diverse and dynamic nature of the attendee population. Every year, millions of pilgrims converge from various backgrounds, each carrying unique cultural practices, languages, and expectations that shape their behaviors. This heterogeneity complicates the establishment of standard protocols for crowding, potentially leading to misunderstandings and tension among different groups (Abalkhail & Al Amri, 2022; Haghani et al., 2023). Moreover, the pilgrimage rituals, often conducted simultaneously with limited spatial configurations, can precipitate congestion issues, posing risks to safety and wellbeing. The critical nature of these dynamics highlights the necessity for tailored interventions that consider the specific behaviors and needs of varied demographic segments, ensuring a smoother flow and heightened safety during the pilgrimage. Effective crowd management must therefore pivot beyond generic solutions, adapting to the real-time conditions and evolving collective behaviors of pilgrims throughout the event.

Previous incidents during the Hajj have served as sobering reminders of the catastrophic consequences of inadequate crowd management. Cases of trampling, panics, and loss or separation from groups underscore the urgent need for innovative strategies to ameliorate these challenges(Abdulrahman & Owaidah, 2007). Traditional crowd control measures often rely on static approaches, such as police presence and physical barriers, which have proven insufficient in addressing the causes of overcrowding and disarray. The shifting nature of crowd dynamics necessitates a more fluid response system that can adapt swiftly and effectively as conditions change. This is where the potential of advanced technologies, particularly those that harness real-time data collection and adaptive response mechanisms, emerges as pivotal in enhancing crowd safety and facilitating timely intervention during emergent situations(E. Felemban et al., 2021). Modern solutions must therefore integrate multiple layers of intelligence—both artificial and human—to foster resilience against crowd crises.

Creating a successful crowd management framework for the Hajj pilgrimage requires not only technological innovation but also a strategic alignment between various stakeholders, including religious authorities, local government agencies, and technology providers. Collaborative efforts are essential to ensure that solutions like the Hajj Lab are designed with input from all relevant parties who understand the local context and its complexities. Furthermore, training personnel in the use of these new technologies bolsters operational preparedness, cultivating a workforce adept at responding to the unique challenges posed by millions of pilgrims. The establishment of clear lines of communication across different management entities also enhances situational awareness, enabling swift decision-making during unforeseen events. Ultimately, a holistic approach that melds innovation, training, and cooperative governance will be instrumental in fostering safer pilgrimage experiences, thereby mitigating the inherent risks associated with the massive scale of Hajj.

2.2. Emerging Technologies in Crowd Management: Numerous studies have been conducted to address the complexities of managing large crowds during Hajj, with many focusing on the use of advanced technologies (Al-Shaery et al., 2023; E. A. Felemban et al., 2020; Halboob et al., 2024; Quaium et al., 2023). One of the most common methods is the deployment of closed-circuit television (CCTV) systems combined with computer vision to monitor crowd density and movement in real-time. A study by Al-Salhie et al. (2014) and more recently by Halboob et al. (2024) emphasized the

effectiveness of using CCTV cameras, RFID devices, and mobile apps integrated with image processing software for real-time crowd flow analysis, enabling authorities to monitor, detect, and respond to incidents efficiently. These systems were integrated with heat maps to detect overcrowded areas, allowing authorities to take preemptive action. However, the study noted that this approach often faced limitations due to fixed camera positions and reduced visibility in adverse weather conditions, prompting the need for supplementary technologies.

Another major avenue explored in crowd monitoring research for Hajj involves drones and sensors. Studies, including those by E. A. Felemban et al. (2020), have shown that drones equipped with thermal and visual sensors can capture crowd density data from the air, providing a mobile solution to some of the constraints faced by static cameras. These studies explored the integration of sensor networks with RFID (Radio Frequency Identification) tags worn by pilgrims to track movements and gather data on crowd behavior. This data is processed using IoT (Internet of Things) platforms, allowing for continuous monitoring. Meanwhile, another promising approach involves Routing Protocols and Mobility in Flying Ad-hoc Networks (FANETs), where multiple drones operate in a network to communicate and share data over wide areas. FANETs offer greater flexibility in covering vast, dynamic environments and can be repositioned in real-time to address specific crowd control needs (E. Felemban, 2021). However, challenges remain in ensuring stable communication between UAVs, managing power consumption, and dealing with data synchronization issues.

A third key area of research focuses on the integration of big data analytics and databases for enhanced decision-making in crowd management. Abalkhail and Al Amri (2022) conducted a study on the use of data fusion techniques, combining data from social media, satellite imagery, and ground sensors to create a comprehensive real-time monitoring system. Their research introduced a framework for predictive analytics that uses historical data to forecast crowd movements and potential risks. The framework, implemented within smart city platforms, demonstrated that large datasets could improve the accuracy of crowd behavior predictions. However, the study emphasized the importance of developing robust data infrastructures and databases capable of handling such high volumes of data while ensuring privacy and security.

In recent studies, wearable sensors have been introduced as a promising tool for predicting pilgrim activities and managing crowds during Hajj. The Open Dataset for Predicting Pilgrim Activities provides a comprehensive data set collected through wearable devices that monitor pilgrims' movement, physiological responses, and environmental conditions in real-time (Al-Shaery et al., 2023). These sensors are integrated into a larger network that processes the data using machine learning algorithms, enabling authorities to predict and mitigate potential crowd issues such as bottlenecks or health-related emergencies.

The advantage of wearable sensors lies in their ability to gather individual-level data, providing highly granular insights into crowd behavior. However, limitations such as the need for widespread adoption among pilgrims and potential data overload present challenges. In alignment with the proposal of stratospheric airships for wide-area surveillance, wearable sensors could serve as a complementary technology, enhancing our system by providing detailed, ground-level data that can be integrated with the 3D aerial data collected by the airships. This combination could create a more comprehensive and multi-layered approach to crowd management during Hajj.

These studies illustrate the progressive integration of technologies and databases to address the challenges of crowd management at Hajj. Each method contributes unique capabilities, with a growing trend towards multi-layered, AI-driven systems that incorporate real-time data to enhance both safety and efficiency.

2.3. Stratospheric Airships and AI-Driven Predictive Analytics: Stratospheric airships stand out as the most effective solution for wide-area, real-time surveillance and crowd management (Sharma, 2016). Their high altitude and extended operational duration enable continuous monitoring over large areas without interruption, making them highly efficient for overseeing events like Hajj. Unlike traditional surveillance methods—such as CCTV cameras, drones, or ground-based sensors—which have limited coverage or require frequent maintenance, stratospheric airships are less impacted by environmental conditions like high temperatures or dust, ensuring uninterrupted data collection. Their ability to capture high-resolution 3D data allows for continuous tracking of crowd density, movement, and environmental factors in real time, providing a comprehensive picture of crowd dynamics (Table 1).

Stratospheric airships offer distinct advantages in crowd management, particularly when compared to real-world deployments at other mass gatherings. For example, during the Olympic Games, drones and fixed cameras were used extensively but faced limitations in coverage and operational time, similar to the challenges seen at Mardi Gras in New Orleans, where CCTV and crowd density algorithms struggled with weather adaptability. Stratospheric airships, in contrast, would provide continuous, wide-area surveillance unaffected by such constraints.

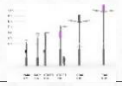
In the Grand Mosque, CCTV and sensors monitor specific bottleneck areas, but airships would enable broader, real-time coverage of larger regions. Similarly, at the Superball festival, drones are restricted by battery life and weather, further highlighting the persistent coverage airships offer. Thus, stratospheric airships, with their ability to gather high-resolution 3D data across vast areas, would greatly enhance Hajj crowd management by filling surveillance gaps and providing uninterrupted monitoring.

When integrated into the Hajj Lab platform alongside traditional technologies, stratospheric airships enhance overall data collection. Aerostats (tethered balloons) offer moderate coverage but are limited by their fixed position and operational height. Drones, while flexible and capable of providing localized data, are restricted by limited battery life and short-range coverage. Helicopters and manned aircraft provide real-time monitoring but are costly and vulnerable to weather conditions.

CCTV cameras and ground-based sensors, though valuable for fixed-location monitoring, have limited spatial coverage and require extensive infrastructure. Satellites, particularly in Low Earth Orbit (LEO), offer broad coverage but are costly and less responsive in real time compared to airships. This multi-tiered approach creates a layered surveillance system, with stratospheric airships providing wide-area coverage and real-time monitoring of the entire pilgrimage route, complementing the more localized surveillance provided by other tools.

The Hajj Lab's strength lies in its AI-driven predictive analytics, which process the vast amounts of data collected by airships, drones, and sensors. AI can analyze crowd behavior, detect anomalies, and predict risks like overcrowding or bottlenecks before they escalate into crises. For example, if crowd density reaches critical levels in a specific area, the AI system can predict the progression and suggest interventions such as rerouting pilgrims. This capability ensures proactive crowd management, reducing the likelihood of dangerous incidents. The integration of these technologies within the Hajj Lab represents a cutting-edge solution, reinforcing Saudi Arabia's leadership in crowd management innovation for large-scale events like Hajj.

Table 5 Aerial Technologies Comparison for Adaption in Hajj Crowd Management (by the Author)

Criteria	On-Site Sensors 	Cameras 	Drones (UAVs) 	Aerostats (Tethered) 	Stratospheric Airships 	Satellites (LEO) 	Satellites (MEO & GEO) 
Coverage Area	Very Limited (specific zones like gates, checkpoints)	Limited (up to 20 km², depending on altitude)	Moderate (up to 50 km²)	Moderate (up to 2000 km²)	Wide (up to 5,000 km²)	Very Wide (up to 10,000 km²)	Extremely Wide (up to 1/3 of the Earth's surface)
Real-time Monitoring	Yes	Yes	Yes	Yes	Yes	Yes (with some delay)	Yes (with some delay)
Operational Duration	Continuous	Continuous (while airborne)	Very Limited (hours due to battery life)	Limited (days to weeks)	Long (weeks to months)	Very Long (years)	Very Long (years)
Data Precision	Moderate (measures specific parameters)	Moderate to High (depending on camera resolution)	High (can be equipped with advanced sensors)	Moderate to High (depends on sensors used)	High (provides high-resolution 3D data)	High (LEO satellites provide detailed imagery)	Moderate to Low (lower resolution, large-scale monitoring)
Cost	Low	Low	Moderate	Moderate	High	Very High	Very High
Infrastructure Requirement	High (dense sensor placement)	High (extensive network of cameras)	Low (requires drones and network infrastructure)	Moderate (requires tethering and ground station)	Moderate (requires launch and monitoring stations)	High (requires ground stations and satellite infrastructure)	Very High (global infrastructure for communication and monitoring)
Environmental Adaptability	Low (environmental factors reduce accuracy)	Low (affected by weather and visibility)	Moderate (affected by weather conditions)	Moderate (tethered, but can be affected by strong winds)	High (less affected by weather at high altitudes)	High (space-based, unaffected by weather)	High (space-based, unaffected by weather)
Mobility/Flexibility	Low (fixed installation)	Low (fixed installation, aerial mobility only)	High (easily redeployed)	Low (tethered, limited mobility)	Moderate (fixed but offers wide coverage)	Low (fixed orbit, limited ability to adjust)	Low (fixed orbit, very large-scale coverage)
Maintenance	Low	Low	High (frequent maintenance for drones)	Low (requires occasional checks)	Low (long operational duration)	Low (typically long-term maintenance-free)	Low (long-term, stable operation)
Ease of Deployment	High (dense sensor network setup)	High (extensive setup and wiring)	Moderate (requires network management)	Moderate (requires tethering and setup)	Low (after initial setup)	Low (requires global infrastructure)	Low (requires global infrastructure)

2.4. The Hajj Lab: Innovating Crowd Management through Integrated Technologies: The synthesis of existing literature reveals a significant gap in the integrated use of technology in crowd management at large-scale events, particularly during the Hajj. Scholars have examined various technologies, highlighting their strengths and weaknesses; however, comprehensive studies focusing on the amalgamation of these methods remain scarce. This indicates a pressing need for an integrated platform that facilitates a more cohesive approach to crowd management, combining these technologies with innovative solutions. A more holistic method not only enhances the real-time collection of data but also optimizes the analytic capabilities, providing stakeholders with timely interventions that are crucial for ensuring the safety and well-being of millions of pilgrims during the Hajj season.

To further explore this area, foundational frameworks in crowd management literature have increasingly highlighted the necessity for adaptive, real-time systems capable of responding to dynamic conditions in mass gatherings. Current studies advocate that successful crowd management requires continuous monitoring and immediate data analysis to preemptively address congestion and potential safety hazards (E. Felemban et al., 2021). Thus, this research investigates the potential of the Hajj Lab as an integrated platform merging traditional crowd management techniques with advanced aerial surveillance. By adopting a cross-disciplinary approach, it entails utilizing theories from urban planning, artificial

intelligence, and crisis management to propose a comprehensive model. This model not only emphasizes data collection and analysis but also focuses on fostering a proactive mindset among authorities and stakeholders, enabling them to anticipate and mitigate risks associated with large crowd gatherings, particularly in a multi-faceted context like that of Hajj.

Figure 1: A Multi-Layered Surveillance System Integrating Stratospheric Airships, Drones, and AI for Real-Time Crowd Management and Environmental Monitoring during Hajj (By Author).

As these theories and technologies converge within the framework of the Hajj Lab, it becomes essential to outline the expected outcomes of this research. Key indicators include improved real-time situational awareness, enhanced predictive capabilities for crowd behavior, and the development of actionable interventions based on structured data analyses. The implications of this integrated approach extend beyond immediate crowd management challenges; they also hold promise for long-term urban development planning in pilgrimage sites. By understanding pilgrim movement patterns and emerging trends in crowd dynamics, authorities can make informed decisions that enhance both safety and the overall pilgrimage experience. In conclusion, this study not only contributes to the existing body of knowledge on crowd management but also proposes a forward-thinking framework that echoes the importance of technological integration and interdisciplinary collaboration in addressing complex, large-scale events like the Hajj.

2.5. Theoretical Framework for Real-Time Crowd Management: The Case of the Hajj Lab": The Hajj Lab draws from several interdisciplinary theories and principles in urban management, surveillance technologies, and crowd dynamics to establish an innovative platform for large-scale event monitoring. At its core, the Hajj Lab is designed to address the complex challenges of managing millions of pilgrims through the integration of smart city principles with real-time monitoring technologies. This theoretical framework is based on the understanding that urban spaces, especially during large-scale events like Hajj, require dynamic, responsive systems capable of adapting to fluid crowd behaviors and environmental conditions.

By adopting principles from urban informatics and situational awareness, the Hajj Lab emphasizes the need for continuous data collection and proactive intervention to ensure safety and efficiency. A key component of the framework is systems integration theory, which emphasizes the interaction between various technological layers, including aerial surveillance (stratospheric airships and drones), ground-based sensors, and human inputs. Each of these layers is interdependent, providing complementary data that, when integrated, offer a holistic view of crowd dynamics. This aligns with socio-technical systems theory, which highlights the need to design infrastructures that account for both technological capabilities and human behavior. The Hajj Lab operationalizes this by incorporating AI and machine

learning algorithms that process large volumes of data to predict crowd behavior, optimize movement, and prevent dangerous overcrowding.

Furthermore, the platform's design leverages crowd psychology and predictive analytics theories, recognizing that crowd movement is not purely spontaneous but often follows predictable patterns based on environmental stimulation, congestion points, and group behavior. Drawing from these concepts, the Hajj Lab's AI models are built to identify patterns and anticipate risks before they manifest into critical situations. By adopting this theoretical framework, the Hajj Lab not only serves as an advanced technological solution but also as an embodiment of principles that fuse urban planning, crowd management, and intelligent data systems to create a robust response to the unique challenges posed by the Hajj pilgrimage.

3. Methodology

This study employs an exploratory research design to develop a theoretical framework for the Hajj Lab, which builds on the concept of the urban lab and adapts it to the unique context of the Hajj pilgrimage. The Hajj Lab represents a novel application of the urban lab model, integrating advanced technologies for real-time crowd management. Specifically, this research explores the potential of aerial surveillance technologies, AI-driven crowd monitoring, and other innovative tools tailored for the Hajj environment. A key focus of the study is identifying and evaluating technologies that can be adapted for Hajj crowd management. This includes the deployment of a multi-layered technological approach involving drones, cameras, sensors, and stratospheric airships. These technologies are proposed as a longitudinal platform for real-time surveillance and data collection across critical locations like Arafat, Muzdalifah, and Mina. By layering these tools, we aim to provide a comprehensive system that ensures the safety and management of millions of pilgrims.

As a conceptual study, we explore how real-time data from these aerial platforms can be integrated with AI systems to optimize crowd behavior prediction and intervention. This layered technological framework represents a forward-thinking approach to managing large-scale crowds, emphasizing the adaptation and adoption of existing technologies in the unique and complex context of the Hajj pilgrimage

3.1. Research Design: The study builds on existing literature across multiple disciplines, including urban labs, AI-driven crowd monitoring, and aerial surveillance technologies, to explore how these concepts can be adapted to the unique context of the Hajj pilgrimage. Rather than testing predefined hypotheses, the design emphasizes a flexible, investigative approach that allows for the integration of innovative ideas and technologies specifically suited for crowd management in mass gatherings. The research design focuses on identifying and evaluating technologies that can be tailored to the complex and dynamic environment of the Hajj. By exploring the potential of a multi-layered technological system—involving drones, cameras, sensors, and stratospheric airships—this study aims to build a conceptual model that enhances real-time situational awareness and predictive crowd behavior monitoring. This layered system is proposed as a solution for managing crowd density and ensuring safety at key locations, such as Arafat, Muzdalifah, and Mina, laying the foundation for future practical applications of the Hajj Lab.

3.2. Data Collection Methods: As an exploratory study, secondary data from existing literature forms the foundation of the analysis. No primary data is collected; instead, past studies on crowd management technologies, AI integration, and aerial surveillance systems are reviewed. These sources help develop the theoretical model, ensuring the proposed framework is grounded in existing knowledge and applicable to large-scale events like Hajj.

4. Results

4.1. The Hajj Lab and utilization of Stratospheric Airship: The Hajj Lab is a comprehensive platform designed to enhance real-time crowd management during Hajj by integrating data from various sources. Building on Saudi Arabia's expertise in AI-driven crowd control, the platform integrates real-time data analysis and predictive modeling to optimize crowd management strategies. The framework collects information from ground-based sensors, CCTV networks, aerial surveillance via stratospheric airships and drones, and real-time inputs from on-site staff. Ground sensors and CCTV cameras monitor crowd density, movement patterns, and environmental conditions in fixed locations, while aerial technologies provide wide-area coverage and 3D mapping of larger pilgrimage routes. On-site staff, equipped with mobile devices, add ground-level observations and incident reports to the data pool, creating a multi-layered picture of the entire Hajj environment. At the heart of the Hajj Lab is its AI-driven command center, which processes all incoming data to identify trends, detect potential risks, and predict crowd behavior. Similar to how urban labs function in cities, the Hajj Lab applies machine learning models to forecast crowd bottlenecks or overcrowded areas. The platform can suggest proactive interventions like opening new routes or rerouting pilgrims based on these real-time predictions, ensuring that crowd control measures are both anticipatory and responsive. This predictive capability reduces the chance of dangerous incidents and enhances the overall flow and safety of pilgrims.

Figure 2: The Hajj Lab Real time Management Framework – (Developed by Author).

The Hajj Lab's innovation lies in its ability to seamlessly combine multiple data streams into one integrated system, where each technology complements the other. While drones focus on high-density zones and CCTV cameras provide detailed fixed-location monitoring, stratospheric airships offer continuous, wide-area coverage from high altitudes. The AI system fuses all these data inputs to provide a comprehensive dashboard for decision-makers, offering real-time actionable insights. This multi-tiered approach allows authorities to maintain situational awareness across the entire Hajj event, reinforcing Saudi Arabia's leadership in smart crowd management and large-scale event planning.

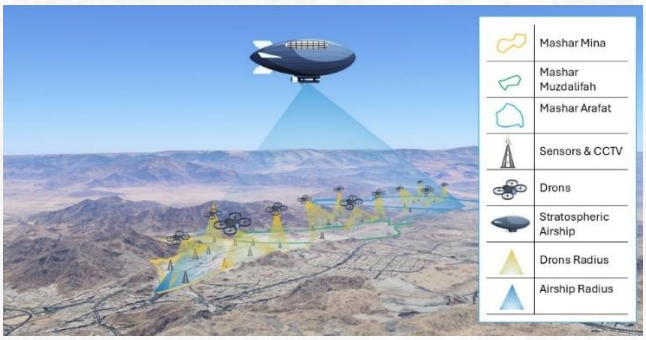


Figure 3 The Hajj Lab: Integrating Multi-Tiered Data Streams for Comprehensive Crowd Management – (Developed by Author)

4.2. Optimization Techniques for Weather Resistance: The design and optimization of stratospheric airships must priorities weather durability to enhance operational efficiency and reliability. A recent study explored the multidisciplinary optimization of solar-powered airships, emphasizing the effectiveness of hybrid algorithms in achieving optimal design solutions (Tang et al., 2023). The research compared the convergence history of different algorithms, including MIGA, NLPQL, and a hybrid approach, finding that the hybrid method demonstrated superior convergence rates and retrieval efficiency.

A comparison between a standard baseline airship and an optimized model revealed significant improvements in key configuration parameters. The optimized airship achieved a 19.83% reduction in volume, a 1.5% decrease in length, and a reduction in mass for critical components such as the solar array, storage battery, and overall energy system. As a result, there was an overall mass reduction of 19.82%, alongside a 9.19% increase in the fineness ratio(Tang et al., 2023) .

The optimization process also placed special emphasis on the layout and positioning of the solar array. The methodology involved integrating various disciplines to develop an optimal design for solar-powered stratospheric airships. By utilizing numerical methods to calculate solar array output power and employing hybrid algorithms for optimization, the research made significant strides toward creating more efficient and weather-resistant designs.

In summary, focusing on weather durability through multidisciplinary strategies and hybrid algorithms is essential for improving the performance and ensuring the reliable operation of stratospheric airships under varying environmental conditions

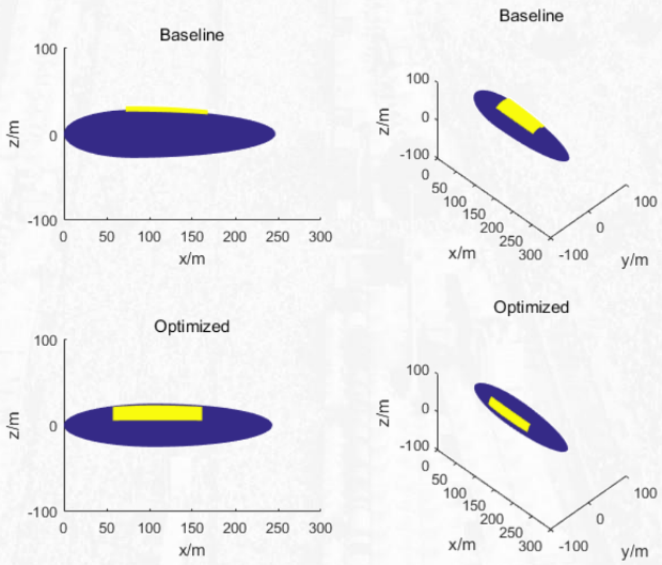


Figure 4: Comparison of the shape and platform of the solar array for baseline and the optimized airship. source: (Tang et al., 2023)

4.3. Design Considerations for Airship Deployment: When designing stratospheric airships for deployment above Arafat, Muzdalifah, and Mina, several critical factors must be considered to ensure effective performance. One of the main considerations is optimizing the airship's design for weather resistance and surveillance capabilities. Solar-powered airships present a challenge in balancing energy collection and consumption, especially given the diverse environmental conditions prevalent in the region. Therefore, it is vital to focus on managing energy efficiently through collection, storage, and consumption to support surveillance missions.

The size and configuration of the airship significantly influence solar energy production efficiency. Adjustments to the airship's dimensions can affect thrust power requirements and the energy generated by solar arrays. Consequently, careful consideration should be given to aligning the power and propulsion systems with aerodynamic needs to achieve an optimal design (Lyu et al., 2024).

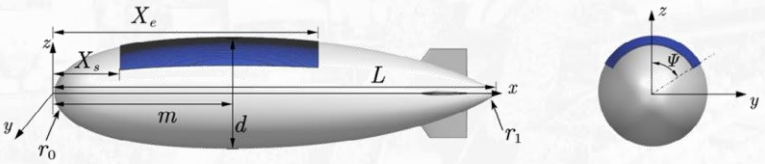


Figure 5. Schematic diagram of the shape parameters of the airship Source (Lyu et al., 2024)

Deployment strategies must also tackle real-time data transmission challenges to facilitate efficient crowd monitoring during Hajj. Establishing robust communication systems that can relay surveillance data from the airships back to central command centers is crucial for timely decision-making and emergency responses.

Integrating the information at the Hajj Lab and the utilization of AI further enhances crowd management by allowing for the analysis of surveillance data to identify potential issues or areas of concern. By incorporating AI algorithms into crowd monitoring systems, decision-makers can obtain actionable insights that aid in proactive planning and response during large-scale events like Hajj. In summary, designing stratospheric airships for the Hajj Lab necessitates a focus on key aspects such as weather resistance, energy management, real-time data transmission, and AI integration. Addressing these elements in the deployment strategy will enhance the capacity to monitor crowds effectively and improve overall decision-making processes during this significant yearly event.

4.4. Challenges and Solutions for Real-Time Data Transmission in the Hajj Lab: Implementing the Hajj Lab as an integrated platform for real-time crowd management presents numerous logistical, operational, and technological challenges. The sheer scale of the Hajj event, which involves millions of pilgrims, requires seamless coordination among diverse stakeholders, including government agencies, private firms, and security teams. Varied interests and conflicting priorities among these groups can lead to inefficiencies and missed opportunities for data sharing and integrated planning. Establishing a collaborative framework is essential but difficult to maintain, especially when trying to align different organizational goals. The complexity of integrating advanced technologies like stratospheric airships, drones, and AI platforms into a single system adds another layer of challenge. Technical reliability is a key concern, as even minor glitches or equipment failures could lead to significant disruptions, underlining the need for robust backup systems and a resilient infrastructure.

A major challenge lies in real-time data transmission. Stratospheric airships, while capable of providing wide-area surveillance, are susceptible to environmental factors such as unpredictable wind conditions, which can affect stability and transmission reliability. To overcome this, trajectory optimization using advanced algorithms like deep reinforcement learning can adjust flight paths dynamically in response to changing conditions. However, regulatory hurdles also arise, as airships require careful coordination with aviation authorities and allocation of airspace, complicating their deployment. Additionally, communication protocols need improvement to handle the large volumes of data generated by drones and airships. Traditional systems that process data only after full reception can cause delays in critical situations. Implementing adaptive communication protocols and enabling partial data processing during transmission can reduce latency and ensure faster decision-making in emergency scenarios.

Beyond technical and logistical challenges, ethical considerations surrounding privacy and data use are paramount in the implementation of the Hajj Lab. The extensive surveillance required for real-time monitoring raises questions about the protection of pilgrims' personal information and the potential misuse of data. Transparent data governance policies and strict ethical oversight mechanisms are necessary to ensure that privacy rights are respected. The perception of constant surveillance could also impact the pilgrims' experience, leading to concerns over privacy violations and reluctance to engage with such technologies. Public education on the benefits of these systems, while addressing privacy concerns, is crucial to ensure trust and cooperation. Developing a comprehensive framework that balances effective crowd management with ethical considerations is essential to the success of the Hajj Lab.

In conclusion, while the Hajj Lab offers innovative solutions for managing the large-scale crowd dynamics of the Hajj pilgrimage, its successful implementation requires careful consideration of technical, logistical, and ethical challenges. By addressing these issues through collaboration, advanced technologies, and transparent policies, the Hajj Lab has the potential to significantly improve crowd management, ensuring the safety and well-being of pilgrims during this important religious event.

5. Discussion

The implications of employing the Hajj Lab as an integrated platform for crowd management during the Hajj are manifold. First and foremost, the fusion of real-time data collection via stratospheric airships with traditional surveillance methods marks a significant advancement in understanding crowd dynamics. This multi-faceted approach not only enhances the accuracy and immediacy of crowd estimates but also enables a more nuanced understanding of pilgrim behaviors and movement patterns. The ability to gather high-resolution 3D data is particularly crucial for identifying potential bottlenecks and high-risk areas, allowing for prompt interventions based on predictive analytics. This aligns with earlier findings that emphasize the necessity of continuous monitoring systems in mass gatherings to mitigate safety hazards (Haghani et al., 2023).

In exploring the operational challenges and benefits of the Hajj Lab platform, it becomes clear that the integration of advanced technologies is paramount. The collaboration between stratospheric airships and ground-based technologies enables a comprehensive monitoring framework that surpasses previous limitations experienced with individual systems. For instance, while drones provide valuable aerial perspectives, their limited operational time and coverage can hinder extensive data gathering. Conversely, stratospheric airships offer a persistent presence, ensuring extensive monitoring capabilities that can inform real-time decision-making processes. This integration of systems enriches data analytics through AI, allowing for the formulation of predictive models that are vital for anticipating crowd movements and mitigating risks before they escalate into crises. This multi-layered surveillance system, therefore, holds the potential to revolutionize the way large-scale crowds are managed, not only during Hajj but also at other significant global events (E. Felemban et al., 2020; Willard R Espy, 2001).

Furthermore, the Hajj Lab's innovative approach to real-time monitoring directly impacts the safety and well-being of millions of pilgrims. As this study suggests, the ability to preemptively identify areas at risk of overcrowding or other dangers can significantly reduce the likelihood of incidents, ensuring a more secure and efficient pilgrimage experience. By leveraging AI-driven predictive analytics, Hajj officials can anticipate problems before they escalate, allowing for proactive management of the crowd (Abalkhail & Al Amri, 2022). This system goes beyond mere response to incidents—it actively enhances situational awareness, enabling authorities to intervene in real time to avoid dangerous scenarios.

Enhancing the AI-driven predictive analytics requires discussing the types of AI models best suited for analyzing crowd behavior in a dynamic environment like Hajj. Recurrent Neural Networks (RNNs), particularly Long Short-Term Memory (LSTM) networks, are well-suited for time-series predictions, allowing them to track crowd movements over time and predict congestion at key locations like the Jamaraat Bridge. Convolutional Neural Networks (CNNs), on the other hand, excel at real-time video analysis, making them ideal for processing video feeds from aerial surveillance and detecting abnormal crowd behavior, such as sudden movements or stampede risks. Combined with reinforcement learning, these models can be adapted for various scenarios. For example, predictive analytics could monitor crowd density at bottlenecks in Arafa in "Nafrah" time and suggest rerouting when necessary, or analyses environmental data to anticipate changes in crowd behavior during extreme weather. In medical emergencies, AI detect early signs of crises and use deep Q-learning to optimise the deployment of medical personnel. These AI systems would enable real-time, proactive interventions, ensuring that the Hajj Lab effectively manages both expected and unexpected challenges.

The operational framework of the Hajj Lab also pioneers new methodologies for crowd management during large-scale events. As noted, the system integrates various technologies, each complementing the other, to provide a holistic view of crowd dynamics. This integrated framework is not limited to Hajj; it holds significant potential for application in other contexts, such as religious festivals, concerts, or public celebrations. With the rising complexity of global events necessitating enhanced safety measures, the methodologies developed through the Hajj Lab may offer critical insights into the future of large-scale event management, providing a blueprint for other venues seeking to improve crowd control measures.

Ultimately, the successful implementation of the Hajj Lab could extend beyond immediate crowd management, informing long-term urban planning and infrastructure development. The data gathered through such a comprehensive system can provide authorities with insights into patterns of crowd movement, helping shape future developments that cater to the needs of mass gatherings. In this sense, the Hajj Lab not only addresses present challenges but also serves as a foundational step towards sustainable crowd management strategies for the future.

6. Conclusion and Recommendation

The Hajj Lab represents a groundbreaking advancement in crowd management, especially for large-scale events like the Hajj pilgrimage. By integrating cutting-edge technologies such as stratospheric airships, drones, and AI-driven analytics, this platform offers a real-time, multi-dimensional view of crowd dynamics that traditional systems cannot achieve. The ability to gather high-resolution 3D data and employ predictive models ensures that authorities can make proactive, data-driven decisions, significantly enhancing the safety and efficiency of managing millions of pilgrims. This marks a major shift in how large-scale crowd events are monitored and managed, moving from reactive to preventive approaches.

The implications of the Hajj Lab extend far beyond immediate crowd control. The data gathered through this integrated platform provides valuable insights that can be used for long-term urban planning and infrastructure development, particularly in areas that regularly host large gatherings. Furthermore, this innovative approach sets a new benchmark for how technology can be leveraged to improve crowd management on a global scale. As the challenges of large-scale events grow, the Hajj Lab offers a scalable model that can be adapted to various contexts, positioning Saudi Arabia as a leader in crowd management innovation.

7. Recommendations and Future Directions

To fully realize the potential of the Hajj Lab, several key areas need to be addressed. First, expanding the application of this framework to other large-scale events will not only enhance its utility but also ensure that the methodologies developed through the Hajj Lab are scalable and adaptable. Collaboration between event organizers, urban planners, and technology providers is essential to fine-tune the system's effectiveness and ensure that it meets the diverse challenges of different environments. Additionally, a strong emphasis must be placed on ethical considerations, particularly in the area of data privacy and surveillance, to build public trust and ensure transparency in the use of advanced monitoring technologies.

1. While initially developed for Hajj, the Hajj Lab framework should be expanded and adapted for use at other mass gatherings, such as global festivals, sporting events, and concerts, where crowd management challenges are similar.
2. Develop cooperative frameworks that bring together urban planners, data scientists, event organizers, and security officials to integrate technology smoothly and address the unique challenges of large-scale events.
3. Implement clear and transparent data governance policies to ensure the ethical collection and use of data, safeguarding privacy and gaining public trust in the deployment of these technologies.

Looking ahead, the Hajj Lab holds immense potential for further development and application. While it has already shown promise in enhancing real-time crowd management during Hajj, there are several areas where this innovative platform can continue to evolve. The integration of new technologies, refinement of predictive models, and focus on sustainability are key to ensuring that the Hajj Lab remains at the forefront of crowd management solutions. Moreover, its potential for informing long-term urban planning and improving infrastructure is vast, allowing for better preparedness and efficiency in handling large-scale events. Expanding the reach of the Hajj Lab beyond Hajj and exploring its use in other global contexts will also be essential for shaping the future of event management.

1. Further develop AI and machine learning algorithms for more accurate predictions of crowd behaviors and early risk detection.
2. Explore eco-friendly technologies, such as solar-powered airships, to reduce the environmental impact of long-duration aerial surveillance.
3. Leverage data collected through the Hajj Lab to inform long-term urban planning strategies, improving infrastructure to better handle large crowds.
4. Position Saudi Arabia as a global leader in crowd management by sharing insights from the Hajj Lab with other international events, setting new standards in large-scale event safety and logistics.

Refrences

- Abalkhail, A. A. A., & Al Amri, S. M. A. (2022). Saudi Arabia's management of the Hajj season through artificial intelligence and sustainability. Sustainability (Switzerland), 14(21), 14142. https://doi.org/10.3390/su142114142
- Alabdulkarim, L., Alrajhi, W., & Aloboud, E. (2016). Urban analytics in crowd management in the context of Hajj. Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), 9742, 249-257. https://doi.org/10.1007/978-3-319-39909-6
- Almoaid, A., & Owaidah, A. (2007). Hajj crowd analysis: Incidents and solutions. M.S. in Information Systems.

- Al-Salhie, L., Al-Zuhair, M., & Al-Wabil, A. (2014). Multimedia surveillance in event detection: Crowd analytics in Hajj. Lecture Notes in Computer Science, 8518, 383-392. https://doi.org/10.1007/978-3-319-13329-4_33
- Al-Shaery, A. M., Ahmed, S. G., Aljassmi, H., Al-Hawsawi, A. N., Maksoud, N., Tridane, A., & Farooqi, N. S. (2023). Open dataset for predicting pilgrim activities for crowd management during Hajj using wearable sensors. Sensors, 23(5), 1025. https://doi.org/10.3390/s23051025
- Al-Wathinani, A., Hertelendy, A. J., Mobrad, A. M., Alhazmi, R., Althunayyan, S., Molloy, M. S., & Goniewicz, K. (2021). Emergency medical providers' knowledge regarding disasters during mass gatherings in Saudi Arabia. Sustainability, 13(6), 3342. https://doi.org/10.3390/su13063342
- Felemban, E. A., Rehman, F. U., Biabani, S. A. A., Ahmad, A., Naseer, A., Majid, A. R. M. A., & Zanjir, F. (2020). Digital revolution for Hajj crowd management: A technology survey. IEEE Access, 8, 208583-208609. https://doi.org/10.1109/ACCESS.2020.3037396
- Felemban, E., Sheikh, A. A., & Naseer, A. (2021). Improving response time for crowd management in Hajj. Computers, 10(4), 46. https://doi.org/10.3390/computers10040046
- Gazzawe, F., & Albahar, M. (2024). How Saudi Arabia is using AI and other high-tech solutions to streamline traffic during Hajj. Heliyon, 10(1).
- Halboob, W., Altaheri, H., Derhab, A., & Almuhtadi, J. (2024). Crowd management intelligence framework: Umrah use case. IEEE Access, 12, 6752-6767. https://doi.org/10.1109/ACCESS.2024.6767
- Haghani, M., Coughlan, M., Crabb, B., Dierickx, A., Feliciani, C., van Gelder, R., & Wilson, A. (2023). 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. https://doi.org/10.1016/j.ssci.2023.106292
- Jabbari, A., Almalki, K. J., Choi, B. Y., & Song, S. (2019). ICE-MoCha: Intelligent crowd engineering using mobility characterization and analytics. Sensors, 19(5), 1025. https://doi.org/10.3390/s19051025
- Khan, K., Albattah, W., Khan, R. U., Qamar, A. M., & Nayab, D. (2020). Advances and trends in real-time visual crowd analysis. Sensors, 20(18), 5287. https://doi.org/10.3390/s20185287
- Liu, S., Zhou, S., Miao, J., Shang, H., Cui, Y., & Lu, Y. (2024). Autonomous trajectory planning method for stratospheric airship regional station-keeping based on deep reinforcement learning. Aerospace, 11(9), 753. https://doi.org/10.3390/aerospace11090753
- Lyu, W., Yang, Y., Miao, J., Cao, S., & Kong, L. (2024). Architecture preliminary design and trade-off optimization of stratospheric airship based on MBSE. Aerospace, 11(7), 753. https://doi.org/10.3390/aerospace11070753
- Quaium, M., Felemban, E., Preko, A., & Abalkhail, A. A. (2023). From pilgrimage to sustainable practice: Leveraging artificial intelligence for the future of Hajj. Journal of Sustainable Tourism.
- Shambour, M. K., & Gutub, A. (2022). Progress of IoT research technologies and applications serving Hajj and Umrah. Arabian Journal for Science and Engineering, 47(2), 1253. https://doi.org/10.1007/s13369-021-05993-4
- Sharma, V., Kumar, N., & Chilamkurti, N. (2016). High-altitude platform for wireless sensor networks and IoT applications: A review. IEEE Communications Surveys & Tutorials.
- Tang, J., Xie, W., Zhou, P., Yang, H., Zhang, T., & Wang, Q. (2023). Multidisciplinary optimization and analysis of stratospheric airships powered by solar arrays. Aerospace, 10(1), 43. https://doi.org/10.3390/aerospace10010043
- Tambo, E., El-Dessouky, A. G., Khater, E. I., & Xianonng, Z. (2020). Enhanced surveillance and response approaches for pilgrims and local Saudi populations against emerging Nipah, Zika, and Ebola viral diseases outbreak threats. Journal of Infection and Public Health, 13(5), 674-678. https://doi.org/10.1016/j.jiph.2020.04.009
- Zhao, H., Thrash, T., Kapadia, M., Wolff, K., Holscher, C., Helbing, D., & Schinazi, V. R. (2020). Assessing crowd management strategies for the 2010 Love Parade disaster using computer simulations and virtual reality. Journal of the Royal Society Interface, 17(167). https://doi.org/10.1098/rsif.2020.0116

Theme of Promoting Health and Safety in Mass Gatherings Management

Assessment of Influenza Vaccine knowledge and uptake by Umrah Visitors

Noura Alshammary[*1], Bayan Alshareef[2], Rehab Gaafr[3] and Heba Dosh[4]

[1*] health care strategy, Madinah Health Cluster

[2]Hajj and Umrah Research, King Abdullah Medical City

[3]Public Health & Preventive Medicine, King Abdullah Medical City

[4]Umm Alquraa University, college of Medicine

[*]Corresponding author: E-mail (dr-noura.saud@hotmail.com)

تقييم المعرفة عن لقاح الإنفلونزا وتلقي اللقاح من قبل المعتمرين

نورا الشمري*[1]، بيان الشريف[2]، رحاب جعفر[3]، هبه دوش[4]

استراتيجيات الرعاية الصحية, تجمع المدينة الصحي*[1]

بحوث الحج والعمرة, مدينة الملك عبدالله الطبية[2]

الصحة العامة والطب الوقائي, مدينة الملك عبدالله الطبية[3]

كلية الطب والجراحة,جامعة ام القري[4]

Abstract

Background/Aim: Umrah is one of the largest annual mass gatherings in the world, presenting substantial public health challenges due to the dense congregations of pilgrims, increasing the risk of respiratory infections. This study evaluates the uptake of influenza vaccinations and the vaccine knowledge among pilgrims in 2024. Materials and Methods: This cross-sectional study surveyed 572 pilgrims in Makkah during Ramadan 2024 using a structured electronic questionnaire. Data collected included demographic details, vaccination history and knowledge of influenza. The study settings included hotels near Masjid Al-Haram, Al-Rajhi Mosque Square, and the train station in Mecca. Results: Among the participants, only 37.8% reported receiving the influenza vaccine. A significantly lower vaccine uptake was observed among pilgrims with chronic diseases (34.3%, p=0.004) compared to healthy individuals. Additionally, males exhibited a higher vaccination rate (44.4%, p=0.005) than females. The association between vaccine knowledge and uptake showed statistical significance; participants with good knowledge had a vaccine uptake rate of 44.7% (p=0.049), contrasting with a 31.8% uptake for those with poor knowledge (p=0.085). Conclusion: Due to limitations in studies highlighting the importance of vaccination for Umrah pilgrims, this study's findings show a critical need for improved health education and intervention strategies to increase influenza vaccine uptake among Umrah pilgrims. Future research should evaluate the effectiveness of tailored health communication strategies over time to enhance preventive behaviors in this high-risk setting.

Keywords: Umrah, influenza vaccination, pilgrims, Saudi Arabia

1. Introduction

Mass gatherings (MGs) according to the World Health Organization, are defined as an assembly of people for a specific purpose in a particular area for a set period that has the potential to strain the planning and response resources of the

host country or community (1). Umrah is one of the largest annual mass gatherings in the world, and every year, millions of Muslims from all over the world gather in Saudi Arabia (2). According to the information provided by the Ministry of Hajj and Umrah for internal and exterior pilgrims, there were 24,715,307 pilgrims in 2022 (3). Overcrowding at Umrah has a significant risk of acquisition and transmission and development of respiratory illnesses. Promoting vaccination among pilgrims can significantly reduce the risk of outbreaks, protect vulnerable populations, and ensure the safety of both participants and local communities(4) (5). Several studies have documented the importance of influenza vaccination during mass gatherings (6) (7) (8). Influenza vaccine uptake is closely linked to the level of knowledge and awareness about the vaccine among individuals. Research consistently shows that people who understand the benefits of the influenza vaccine are more likely to get vaccinated. Influenza vaccination is mandatory for pilgrims participating in the Hajj, reflecting the Saudi government's commitment to public health during this large-scale religious gathering. In contrast, the Umrah pilgrimage does not have a similar vaccination mandate. This discrepancy highlights the need for greater awareness and voluntary vaccination efforts for Umrah pilgrims, as they also face similar risks in crowded settings, albeit on a smaller scale. Therefore, this study aims to measure the vaccine uptake among pilgrims during Umrah and to assess the knowledge of the influenza vaccine.

2. Methodology (Materials and methods)

This study employs a cross-sectional design focused on Umrah pilgrims in Makkah, Saudi Arabia, during the 2024 Umrah season. The target population included all individuals participating in Umrah in 2024. Inclusion criteria consist of participants aged 18 years and older, regardless of gender, who visited the Holy Masjid during the Umrah season. Exclusion criteria will apply to individuals who do not meet the eligibility criteria and those who do not speak either English or Arabic. Data was collected with a survey targeted any Muslim visiting the Holy Masjid in 2024. Convenience method of sampling was used to recruit participants.

A valid and reliable questionnaire was used and it was available in both Arabic and English, distributed via Google Forms. The questionnaire has 3 parts: part one included questions related to demographics, including age, gender, marital status, the field of education, and questions related to flu vaccination status. Part two of the questionnaire consisted of thirteen true and false statements related to the knowledge of pilgrims about the flu vaccine. These items were 1 for correct answers and 0 for wrong and do not know responses. The maximum cumulative knowledge score was 13. The knowledge score was further categorized into three levels, i.e., poor knowledge (score 5), moderate knowledge (score 6 to 9), and good knowledge (score 10). Part three consisted of questions identifying the barriers influencing the receipt of the flu vaccine. Data was recorded in an Excel sheet, with subsequent analysis performed using SPSS software version 23. The Ethical approval was obtained from King Abdullah Medical City.

3. Results and Discussion

A total of 572 individuals who visited Makkah for Umrah performance were involved in this study, Table 1 shows the demographic characteristics of participants in the study, (n=284, 69.9%) of the sample were Saudi, while Egyptian represent (n=45,7.9%) of them. There was an almost equal distribution of males (n=284,49.7%) and females (n=288,50.3%) gender.

The mean age of our participants is 35 ± 13. Regarding education level, (n= 275, 48.1%) of our sample had a bachelor's degree, while secondary school or less and master's degree or above represent (n=58,10.1%), (n= 58,10.1%) respectively. Most of the participants free of chronic diseases (n= 440,76.9%).

Table 1: Demographic data of participants		Frequency	%
Nationalities	Saudi	398	69.6
	Egyptian	45	7.9
	Algerian	12	2.1
	Moroccan	13	2.3
	Kuwaiti	11	1.9
	Emirati	14	2.4
	Omani	4	0.7
	American	4	0.7
	British	3	0.5
	Yemeni	14	2.4
	Jordan	8	1.4
	Syrian	5	0.9
	Iraqi	2	0.3
	Indian	4	0.7
	Pakistani	3	0.5
	Sudanese	4	0.7
	Somali	3	0.5
	South East of Asia	6	1.0
	Other	14	2.4
Gender	Male	284	49.7
	Female	288	50.3
Education level	Secondary school or less	58	10.1
	high school/ Diploma	181	31.6
	Bachelor's	275	48.1
	Master's degree and above	58	10.1
Chronic diseases	No chronic diseases	440	76.9
	two chronic diseases or more	24	4.2
	HTN or DM2	56	9.8
	BA	25	4.4
	other	27	4.7

As shown in Table 2, Most of the participants (356,62.2%) did not receive influenza vaccine. Regarding influenza vaccine knowledge, almost half of the participants had moderate knowledge (n=290,50.7%) while only (n=103,18%) had good knowledge.

Table (2): influenza vaccine uptake and Knowledge		Frequency	%
Vaccination status	Not vaccinated	356	62.2
	Influenza vaccination	216	37.8
Vaccine knowledge	Poor knowledge	179	31.3
	Moderate knowledge	290	50.7
	Good knowledge	103	18.0

The results show that, the influenza vaccine uptakes are higher among healthy individuals (n= 65, 49.2%), otherwise, the majority of participants with chronic diseases did not uptake the influenza vaccine (n=289,65.7%) table (3).

Table (3): association of influenza vaccine uptake and other variables

Variable		influenza vaccine status		
		Not vaccinated	Vaccinated	*P*-value
Chronic dx	Yes	289(65.7%)	151(34.3%)	0.002
	No	67(50.8%)	65(49.2%)	
Gender	Male	158 (55.6%)	126(44.4%)	0.001
	Female	198(68.8%)	90(31.3%)	

Nationality	Saudi	261(65.6%)	137(34.4%)	0.013
	Non-Saudi	95(54.6%)	79(45.4%)	
Influenza vaccine Knowledge	Poor	122(68.2%)	57(31.8%)	0.085
	Moderate	177(61.0%)	113(39.0%)	
	Good	57(55.3%)	46(44.7%)	

Table 4 provides insights into potential predictors of influenza vaccine uptake among the study participants. Although it suggested higher odds of influenza vaccine uptake among Males, indicating a potential gender-related trend (P=0.005).

Table 4: Findings of logistic regression model for potential predictors of influenza vaccine uptake					95% C.I.	
Predictors	Category	Reference group	P value	Odd ratio	Lower	Upper
Gender	Male	Female	0.005	0.607	.427	.863
Saudi	Saudi	Non-Saudi	.149	1.054	.981	1.131
Chronic diseases	Absent	Present	.004	1.798	1.205	2.683
knowledge	Moderate	Good	.049	.599	.359	.999
	Poor	Good	.447	.835	.525	1.329

Our study reveals that a substantial majority of participants (62.2%) did not receive the influenza vaccine. This rate of non-vaccination is concerning given the crowded conditions of Umrah, which facilitate the rapid spread of respiratory infections. These findings align with previous research indicating varying rates of vaccine uptake among pilgrims, often influenced by factors, such as national vaccination policies and public health campaigns in their home countries (4). For instance, a study on Malaysian pilgrims during the 2018 Hajj season showed a comparable low rate of influenza vaccination, which was attributed to limited access to vaccines and variable public health strategies across different regions (11). The influenza vaccine uptake among participants was relatively low, with only 37.8% reporting having received the vaccine, as shown in Table 2. This low uptake rate is concerning, given the potential for influenza outbreaks in mass gatherings.

Our logistic regression model indicated that gender was a significant predictor of influenza vaccine uptake, with males showing higher odds of receiving the vaccine compared to females. This finding aligns with existing literature suggesting that men are generally more likely to get vaccinated than women. Schmid et al. (2017) have highlighted gender differences in health behaviors, noting that women often exhibit higher levels of vaccine hesitancy due to concerns about side effects and doubts about vaccine efficacy (23). Nationality was not found to be a statistically significant predictor of influenza vaccine uptake in our study. This suggests that, within our sample, nationality did not play a substantial role in influencing vaccination behavior. This finding contrasts with some previous studies that have reported significant differences in vaccine uptake based on nationality, often attributed to variations in healthcare access, cultural beliefs, and health literacy (21,26). The presence of chronic diseases was found to be a significant predictor, with healthy participants being more likely to receive the vaccine (odds ratio = 1.798, p = 0.004). This is an important observation as it highlights the need for targeted interventions to encourage vaccination among those with chronic conditions, who are at a higher risk of severe complications from influenza (23). The presence of chronic diseases was found to be a significant predictor, with healthy participants being more likely to receive the vaccine (odds ratio = 1.798, p = 0.004). This is an important observation as it highlights the need for targeted interventions to encourage vaccination among those with chronic conditions, who are at a higher risk of severe complications from influenza (23).

Regarding vaccine knowledge, our results indicated that only a small rate of participants (18%) had good knowledge about the influenza vaccine, while approximately half had moderate knowledge (50.7%). This level of awareness is critical, as it directly impacts the likelihood of vaccine uptake. Comparable studies have shown similar patterns, where

knowledge gaps significantly contribute to low vaccination rates. For instance, research conducted by Barasheet et al. (2014) during the 2014 Hajj season observed that enhanced educational efforts following the H1N1 pandemic led to increased awareness and vaccination rates among pilgrims from certain countries (18). In particular, a study by Haridi et al. (2017) found that individuals with higher knowledge levels about influenza and its vaccine were more likely to be vaccinated (19). A study by Alqahtani et al. (2019) on Hajj pilgrims found similar trends, where increased knowledge about the influenza vaccine correlated with higher vaccination rates (20). Furthermore, the demographic characteristics influencing vaccine uptake in our study mirror those observed in previous research. A study by Memish et al. (2015) has documented that higher educational levels and the absence of chronic diseases are associated with better preventive practices, including vaccination (21).

This study's limitations include potential biases stemming from the use of a self-administered questionnaire, which may lead to self-reporting inaccuracies. The sample might not fully represent all pilgrims' demographics, particularly those from diverse socio-economic backgrounds or varying educational levels. Additionally, the cross-sectional nature of the study limits the ability to establish causality between observed behaviors and influenza vaccination uptake. Further research might need to employ a longitudinal approach to better understand changes in pilgrim behavior over time and the impact of interventions.

4. Conclusions

Enhanced influenza vaccine uptake and improved preventive practices are essential for Umrah pilgrims, given the challenges posed by these mass gatherings. To achieve higher vaccination rates and better health outcomes, there is a pressing need for more effective educational campaigns that are tailored to the diverse cultural and linguistic backgrounds of pilgrims. Many pilgrims may be unaware of the risks associated with influenza, especially in crowded settings. To address this, health authorities can implement targeted educational campaigns that provide information about the benefits of vaccination and potential health risks during the pilgrimage. Moreover, offering on-site vaccination clinics at departure points and providing easy access to vaccines can significantly increase uptake. Collaborating with religious leaders or mosques Imams, Umrah companies and tourism companies to spread awareness during community gatherings can also encourage more pilgrims to get vaccinated, ensuring a safer experience. Future directions should include implementing longitudinal studies to assess the long-term efficacy of these interventions and exploring innovative communication strategies to address persistent barriers to vaccine acceptance. Such efforts are crucial for safeguarding the health of pilgrims and preventing the spread of infectious diseases during these significant religious events.

References

1. Hoang VT, Gautret P. Infectious Diseases and Mass Gatherings. Curr Infect Dis Rep [Internet]. 2018;20(11):44. Available from: https://doi.org/10.1007/s11908-018-0650-9
2. Mahdi HA, Assaggaf HM, Alfelali M, Ahmed OB, Alsafi R, Shaban RZ, et al. Hand hygiene knowledge, perception, and practices among domestic visitors to the prophet's mosque in al madinah city amid the covid-19 pandemic: A cross-sectional study. Int J Environ Res Public Health. 2021;18(2):1–11.
3. General Authority for Statistics. Umrah statistics publication [Internet]. 2024 [cited 2024 Jul 19]. Available from: https://www.stats.gov.sa/en/862

4. Alfelali M, Barasheed O, Badahdah AM, Bokhary H, Azeem MI, Habeebullah T, et al. Influenza vaccination among Saudi Hajj pilgrims: Revealing the uptake and vaccination barriers. Vaccine [Internet]. 2018;36(16):2112–8. Available from: https://www.sciencedirect.com/science/article/pii/S0264410X18303438
5. Alasmari AK, Edwards PJ, Assiri AM, Behrens RH, Bustinduy AL. Use of face masks and other personal preventive measures by Hajj pilgrims and their impact on health problems during the Hajj. J Travel Med [Internet]. 2020 Dec 1;27(8):taaa155. Available from: https://doi.org/10.1093/jtm/taaa155
6. Mahdi H, Alqahtani A, Barasheed O, Alemam A, Alhakami M, Gadah I, et al. Hand hygiene knowledge and practices among domestic hajj pilgrims: implications for future mass gatherings amidst COVID-19. Trop Med Infect Dis. 2020;5(4).
7. Tobaiqy M, Alhasan AH, Shams MM, Amer SA, Maclure K, Alcattan MF, et al. Assessment of preventative measures practice among umrah pilgrims in saudi arabia, 1440h-2019. Int J Environ Res Public Health. 2021;18(1):1–16.
8. OpenEpi Menu. Open Source Epidemiologic Statistics for Public Health [Internet]. 2022 [cited 2024 Jul 19]. Available from: https://www.openepi.com/Menu/OE_Menu.htm
9. Benkouiten S, Brouqui P, Gautret P. Non-pharmaceutical interventions for the prevention of respiratory tract infections during Hajj pilgrimage. Travel Med Infect Dis [Internet]. 2014;12(5):429–42. Available from: https://www.sciencedirect.com/science/article/pii/S1477893914001227
10. Commodari E. The Role of Sociodemographic and Psychological Variables on Risk Perception of the Flu. Sage Open [Internet]. 2017 Jul 1;7(3):2158244017718890. Available from: https://doi.org/10.1177/2158244017718890
11. Dauda Goni M, Hasan H, Naing NN, Wan-Arfah N, Zeiny Deris Z, Nor Arifin W, et al. Assessment of Knowledge, Attitude and Practice towards Prevention of Respiratory Tract Infections among Hajj and Umrah Pilgrims from Malaysia in 2018. Vol. 16, International Journal of Environmental Research and Public Health. 2019.
12. Ridda I, Mansoor S, Briggs R, Gishe J, Aatmn D. Preparedness for Mass Gathering During Hajj and Umrah BT - Handbook of Healthcare in the Arab World. In: Laher I, editor. Cham: Springer International Publishing; 2021. p. 1215–35. Available from: https://doi.org/10.1007/978-3-030-36811-1_48
13. Alfelali M, Koul PA, Rashid H. Pandemic Viruses at Hajj: Influenza and COVID-19 BT - Handbook of Healthcare in the Arab World. In: Laher I, editor. Cham: Springer International Publishing; 2021. p. 1249–66. Available from: https://doi.org/10.1007/978-3-030-36811-1_50
14. Salim Parker JG. CDC Yellow Book 2024. 2024 [cited 2024 Jul 19]. Saudi Arabia: Hajj & Umrah Pilgrimages. Available from: https://wwwnc.cdc.gov/travel/yellowbook/2024/itineraries/saudi-arabia-hajj-and-umrah-pilgrimages
15. Hashim S, Ayub ZN, Mohamed Z, Hasan H, Harun A, Ismail N, et al. The prevalence and preventive measures of the respiratory illness among Malaysian pilgrims in 2013 hajj season. J Travel Med [Internet]. 2016 Mar 1;23(2):tav019. Available from: https://doi.org/10.1093/jtm/tav019
16. Alfelali M, Barasheed O, Koul P, Badahdah AM, Bokhary H, Tashani M, et al. Influenza vaccine effectiveness among Hajj pilgrims: a test-negative case-control analysis of data from different Hajj years. Expert Rev Vaccines [Internet]. 2019 Oct 3;18(10):1103–14. Available from: https://doi.org/10.1080/14760584.2019.1646130
17. Barry MA, Aljammaz KI, Alrashed AA. Knowledge, Attitude, and Barriers Influencing Seasonal Influenza Vaccination Uptake. Can J Infect Dis Med Microbiol [Internet]. 2020 Jan 1;2020(1):7653745. Available from: https://doi.org/10.1155/2020/7653745
18. Barasheed O, Rashid H, Heron L, Ridda I, Haworth E, Nguyen-Van-Tam J, et al. Influenza Vaccination Among Australian Hajj Pilgrims: Uptake, Attitudes, and Barriers. J Travel Med [Internet]. 2014 Nov 1;21(6):384–90. Available from: https://doi.org/10.1111/jtm.12146
19. Haridi HK, Salman KA, Basaif EA, Al-Skaibi DK. Influenza vaccine uptake, determinants, motivators, and barriers of the vaccine receipt among healthcare workers in a tertiary care hospital in Saudi Arabia. J Hosp Infect [Internet]. 2017;96(3):268–75. Available from: https://www.sciencedirect.com/science/article/pii/S0195670117300919

20. Alqahtani AS, Althimiri NA, BinDhim NF. Saudi Hajj pilgrims' preparation and uptake of health preventive measures during Hajj 2017. J Infect Public Health [Internet]. 2019;12(6):772–6. Available from: https://www.sciencedirect.com/science/article/pii/S1876034119301406
21. Memish ZA, Assiri A, Turkestani A, Yezli S, al Masri M, Charrel R, et al. Mass gathering and globalization of respiratory pathogens during the 2013 Hajj. Clin Microbiol Infect [Internet]. 2015;21(6):571.e1-571.e8. Available from: https://www.sciencedirect.com/science/article/pii/S1198743X15002967
22. Alhajji M, Alzeer AH, Al-Jafar R, Alshehri R, Alyahya S, Alsuhaibani S, et al. A national nudge study of differently framed messages to increase COVID-19 vaccine uptake in Saudi Arabia: A randomized controlled trial. Saudi Pharm J [Internet]. 2023;31(9):101748. Available from: https://www.sciencedirect.com/science/article/pii/S1319016423002438
23. Schmid P, Rauber D, Betsch C, Lidolt G, Denker ML. Barriers of Influenza Vaccination Intention and Behavior — A Systematic Review of Influenza Vaccine Hesitancy, 2005 — 2016. PLoS One [Internet]. 2017 Jan 26;12(1):e0170550. Available from: https://doi.org/10.1371/journal.pone.0170550
24. Alaamri O, Okmi EA, Suliman Y. Vaccine Hesitancy in Saudi Arabia: A Cross-Sectional Study. Vol. 7, Tropical Medicine and Infectious Disease. 2022.
25. Godinho CA, Yardley L, Marcu A, Mowbray F, Beard E, Michie S. Increasing the intent to receive a pandemic influenza vaccination: Testing the impact of theory-based messages. Prev Med (Baltim) [Internet]. 2016;89:104–11. Available from: https://www.sciencedirect.com/science/article/pii/S0091743516301086
26. Alotaibi BM, Yezli S, Bin Saeed AAA, Turkestani A, Alawam AH, Bieh KL. Strengthening health security at the Hajj mass gatherings: characteristics of the infectious diseases surveillance systems operational during the 2015 Hajj. J Travel Med [Internet]. 2017 May 1;24(3):taw087. Available from: https://doi.org/10.1093/jtm/taw087

Proactive Health Interventions for Hajj Pilgrims Using IoT and AI

Mohammad Jassas, Ghada Alfattni*, Atheer Alhozali, Sara Alqurashi, Manar Aljohani, Mariam Khuzaie, Wed Alharbi

Computer Science Department, Jamum University College, Umm Alqura University

*Corresponding author: E-mail (gafattni@uqu.edu.sa)

نظام التدخلات الصحية الاستباقية لحجاج بيت الله الحرام باستخدام إنترنت الأشياء والذكاء الاصطناعي

محمد شرف جساس، غادةالفتني*، أثيرالهذلي، سارةالقرشي، منارالجهني، ريم الخزاعي، ود الحربي

قسم علوم الحاسب، الكلية الجامعية بالجموم، جامعة ام القري

Abstract

This study presents a novel health monitoring system designed to enhance the safety and well-being of pilgrims during the Hajj pilgrimage. The system leverages Internet of Things (IoT) devices, Artificial Intelligence (AI), and edge computing to enable real-time health data collection, analysis, and prediction. Wearable sensors, such as Bluetooth Low Energy (BLE) devices, continuously monitor vital signs like body temperature and blood oxygen levels. This data is transmitted to a mobile application and processed on an edge computing server, where advanced machine learning algorithms, including Random Forest and Artificial Neural Networks (ANNs), predict potential health risks. A dynamic task scheduling mechanism optimizes resource allocation, minimizing delays. By distributing computational tasks intelligently between cloud and edge environments, the system ensures efficient processing and timely alerts. Results demonstrated that Artificial Neural Networks (ANN) and Random Forest (RF) models were the strongest performers, with ANN achieving 72% accuracy, while RF showed balanced performance across metrics. The study recommends refining machine learning models using larger, diverse datasets and exploring advanced AI techniques to enhance predictive capabilities. The proposed system provides a proactive approach to healthcare during Hajj, offering early warnings for health issues and enabling timely interventions, which improves the overall pilgrimage experience and reduces the burden on medical personnel.

Keywords: Machine Learning, eHealth System, IoT, Hajj, Pilgrims, Health Monitoring

1. Introduction

The annual increase in the number of pilgrims and Umrah performers has created a pressing need for advanced healthcare systems capable of accurately monitoring and addressing the health needs of millions of pilgrims. Traditional healthcare approaches face significant limitations in managing the scale and complexity of health concerns during the Hajj pilgrimage, where overcrowding and extreme weather conditions place pilgrims at high risk for various health problems, including heatstroke, respiratory issues, and infectious diseases. In response to these challenges, the integration of Internet of Things (IoT) and Artificial Intelligence (AI) technologies presents a transformative solution to monitor, analyze, and proactively manage the health of pilgrims in real-time.

Modern IoT and AI technologies allow for the continuous collection and analysis of vital health data, enabling timely medical interventions that improve health outcomes. Wearable sensors, which monitor critical health indicators such as body temperature, heart rate, and blood oxygen levels, form the foundation of this system. These devices, integrated into an IoT-based infrastructure, collect real-time data that is then processed using AI algorithms to predict potential health risks before they escalate. AI's predictive capabilities can alert medical teams of emergencies, allowing for quicker responses and better allocation of healthcare resources. In addition, cloud and edge computing technologies play a pivotal role in ensuring that the massive amounts of data generated by these systems are processed efficiently and securely, facilitating informed and timely decision-making by healthcare providers.

The aim of this study was to evaluate the effectiveness of current IoT and AI-based health monitoring systems in improving healthcare for pilgrims. By reviewing available models and systems, the study also seeks to provide recommendations on how to enhance these technologies to achieve higher standards of safety, efficiency, and reliability in managing pilgrim health.

Thus, this research contributes to the field of pilgrim health management by:

- Developing a comprehensive system for real-time monitoring and analysis of pilgrim health data.
- Utilizing advanced machine learning techniques to accurately predict potential health risk.
- Implement a robust notification system to enable timely medical intervention.
- Providing a valuable tool for healthcare providers to improve the overall well-being of pilgrims.

Literature Review

Advancements in IoT and AI have significantly transformed healthcare, particularly in the realm of real-time health monitoring. IoT-based systems equipped with wearable sensors are widely used to monitor vital signs, predict chronic health issues, and offer personalized care through continuous data analysis (1,2). These systems have proven their value in various settings, especially during the COVID-19 pandemic, where remote monitoring and disease classification helped mitigate the spread of the virus while maintaining patient care (3). Beyond healthcare, IoT technologies have also been successfully applied in high-risk industries such as mining and manual scavenging, where real-time monitoring of workers' health and environmental conditions ensures safety (4). The integration of IoT and AI in healthcare has shown significant benefits, such as improving patient outcomes, reducing hospital stays, and enabling proactive interventions (5,6). During mass gatherings like the Hajj, these benefits are particularly valuable. Wearable devices, for instance, continuously monitor pilgrims' vital signs, including heart rate, blood pressure, and oxygen saturation, providing medical teams with critical data to assess emergency situations in real time (7,8). Machine learning (ML) models are then employed to analyze this data, automatically classifying emergency levels and prioritizing cases based on severity.

Research has also demonstrated the utility of IoT-enabled wearable devices in emergency settings, such as mass casualty incidents. These devices provide remote monitoring and automated triage, allowing for more efficient patient prioritization and faster medical response times (9). Specific sensor technologies, such as ceramic piezoelectric disks, have been developed to detect cardiac and respiratory events, offering enhanced accuracy in critical care scenarios (10).

In addition to real-time monitoring, AI-driven machine learning models have proven effective in improving triage processes in emergency departments. Studies have shown that these models can predict important health outcomes such as mortality rates, critical care needs, and hospitalization risks with high accuracy (11,12). Algorithms like XGBoost,

Random Forest, and Deep Neural Networks have been found to outperform traditional triage methods, making them valuable tools for predicting emergency levels based on patient data (13,14). Moreover, explainable AI techniques help increase transparency and trust in AI-based triage systems, which is crucial for widespread adoption in healthcare settings (12).

While existing studies have explored various aspects of pilgrim health management, a significant gap remains in the development of a comprehensive system that integrates real-time monitoring, predictive analytics, and efficient notification mechanisms. This research aims to address this gap by proposing a novel framework that combines these elements to enhance the overall effectiveness of pilgrim healthcare services. The use of IoT and AI technologies in proactive healthcare interventions during mass gatherings such as the Hajj has the potential to significantly reduce health risks, improve emergency response times, and enhance overall healthcare delivery. By leveraging real-time monitoring, predictive analytics, and machine learning, these systems offer a comprehensive approach to managing health during large-scale events. This study will further explore the effectiveness of these technologies in providing proactive healthcare solutions for Hajj pilgrims, with a focus on improving safety and optimizing healthcare resource allocation.

2. Methodology

2.1 System Architecture

The proposed system is designed to monitor the health status of Hajj pilgrims in real-time by collecting and analyzing data using IoT-based sensors, edge computing, and cloud platforms. It aims to predict potential health emergencies and send alerts to healthcare providers for immediate intervention. This methodology integrates data collection, analysis, and machine learning models to ensure accurate predictions and timely health interventions. The overall system architecture consists of three core components: IoT devices, Edge Computing, and a Cloud, as shown in Figure 1.

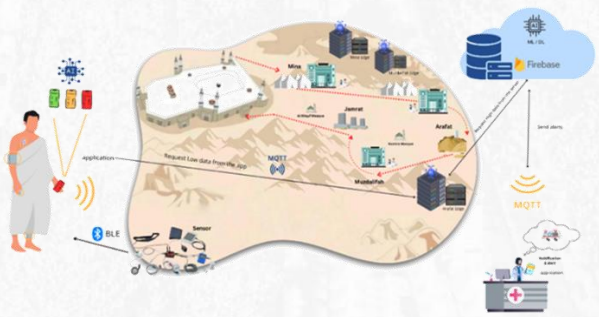


Figure 12: System Architecture

Edge Computing efficiently processes data from medical sensors, wearable devices, and smartphones, handling tasks that require more computational power than available locally. This involves offloading certain processing and analysis tasks, especially for moderate or abnormal readings, to the local server using MQTT. The server employs advanced AI techniques for pattern analysis, identifying critical health conditions that demand immediate attention. Edge computing excels at processing large volumes of data through distributed tasks across multiple nodes. Each node can handle data from multiple sensors simultaneously, ensuring uninterrupted and rapid processing even in the face of processing congestion or connectivity issues. This architecture enables the system to adapt flexibly to varying data loads. Furthermore, the framework can aggregate processed data and transmit it to the cloud using MQTT .

A smart machine learning model is at the heart of this system, accurately predicting patient conditions. The app's success, especially in telling apart emergencies from non-emergencies, depends on this model's skills. We carefully picked the best algorithm to make sure the model can handle everything the app throws at it

Healthcare providers can monitor and track pilgrim data in real-time, allowing doctors and specialists to stay informed. The health data is continuously synchronized from the cloud to a dedicated monitoring dashboard for medical professionals. Physicians can review vital signs to identify health issues and implement preventive measures. They can also determine which cases require immediate response or intervention, with alerts triggered for critical conditions .

At the healthcare provider level, doctors and specialists have access to a real-time dashboard that continuously syncs health data from the cloud. This dashboard allows them to monitor the vital signs of pilgrims and identify potential health risks before they become emergencies. Physicians can make informed decisions regarding preventive measures, and in critical situations, they can trigger immediate medical interventions. Alerts are sent to medical teams based on the system's classification of health data, enabling quick and effective responses.

2.2 Machine Learning Model

The core of the system's functionality lies in the prediction of potential health emergencies using machine learning algorithms. The system collects vast amounts of health data from wearable sensors, and this data is analyzed using AI techniques to predict health risks. The machine learning model must balance accuracy with speed, as timely predictions are critical for proactive healthcare interventions. Various algorithms are evaluated to determine the best-performing model.

The models were trained on a comprehensive dataset[1] containing patient demographics, symptoms, vital signs, and triage outcomes. This dataset includes key health metrics such as heart rate, blood pressure, oxygen levels, and emergency triage decisions, making it ideal for predicting emergency situations among pilgrims. By utilising this data, the machine learning model can accurately classify emergency cases, ensuring rapid alerts and timely medical interventions. The model's training focused on optimizing algorithms like Random Forest and XGBoost to achieve high accuracy in predicting critical health events based on real-time data collected from wearable devices.

The evaluation of the models was based on the following key metrics:

- Accuracy: The overall ratio of correct predictions. Although high accuracy is a positive indicator, it does not guarantee superior model performance when dealing with class imbalances.
- Precision: Measures the proportion of true positive identifications, focusing on reducing false positives.
- Recall: Reflects the model's ability to capture true positive instances, which is critical for minimizing false negatives.
- F1-Score: A harmonic mean of precision and recall, offering a balanced measure of a model's performance.

The system uses wearable sensors to collect pilgrims' health data, including body temperature, heart rate, and oxygen levels. This data is transmitted in real-time to the edge computing layer for immediate analysis, reducing the need for constant cloud communication and minimizing latency. The edge servers handle most of the processing tasks, applying AI algorithms to detect abnormal patterns in the data. For larger datasets or more complex analysis, the data is sent to the cloud for further processing. By combining real-time data from individual pilgrims with aggregated data from the entire

[1] https://www.kaggle.com/datasets/ilkeryildiz/emergency-service-triage-application

population, the system can predict broader health trends and providing insights into common health issues faced by pilgrims. This predictive capability enables healthcare providers to intervene early and potentially prevent large-scale health crises during the Hajj.

3. Results and Discussion

Data Insights: The dataset used for training the machine learning model contains 1,232 entries with the following features:

- Sex: Coded as integers representing male and female.
- Age: Numeric values representing the age of the patients.
- Systolic Blood Pressure (SBP): Numeric values representing the systolic blood pressure.
- Diastolic Blood Pressure (DBP): Numeric values representing the diastolic blood pressure.
- Heart Rate (HR): Numeric values representing the heart rate.
- Respiratory Rate (RR): Numeric values representing the respiratory rate.
- Body Temperature (BT): Numeric values representing body temperature in degrees Celsius.
- Triage and Acuity Scale (TAS): A numeric value representing the severity level of the patient's condition, which helps determine the urgency of medical care.

These features are crucial in building a predictive model that classifies patients into different urgency levels, allowing medical teams to prioritize cases more effectively.

The data were prepared for training as follows:

- Training set: 985 samples with 7 features (excluding the target variable, TAS, and the non-numeric feature, Chief Complaint.(
- Testing set: 247 samples with 7 features.

The feature importance was evaluated using a Random Forest model. The most important features identified were Age and HR, followed by SBP, DBP, and BT). The TAS classes are relatively balanced: Class 1 (emergency): 52.76% and Class 2 (non-emergency): 47.24%.

Given the slight class imbalance and the need for accurate classification of emergency triage levels, a number of of classifiers were trained to optimize prediction accuracy and ensure reliable medical prioritization during emergency care.

AI Prediction Accuracy: The proposed framework utilizes machine learning models to accurately classify patients into emergency and non-emergency categories. This predictive approach optimizes healthcare resource allocation by focusing resources on urgent cases and minimizing unnecessary treatments, thereby significantly enhancing patient outcomes. The model is designed to complement cloud-IoT systems by efficiently utilizing computational resources and improving the overall performance of healthcare infrastructure.

Feature Selection Algorithms

To ensure the model's optimal performance, we initially selected the most relevant features through manual inspection to prevent overfitting. Following this, we employed various feature selection algorithms to further enhance accuracy. These methods included:

- **Feature Importance:** This algorithm was used to rank features based on their contribution to the model, allowing us to retain the most informative features.
- **SelectKBest:** This method selects the top features that have the highest correlation with the target variable, further refining our feature set.
- **Recursive Feature Elimination (RFE):** A technique that recursively removes the least important features, reducing the model's complexity while maintaining performance.

These feature selection strategies enabled the model to focus on critical predictors like Age, HR, SBP, DBP, and BT), which were identified as the most important variables. This process not only improved the model's performance but also reduced the risk of overfitting by eliminating irrelevant features.

Machine Learning Models and Algorithms

Several traditional machine learning models and Artificial Neural Networks (ANNs) were applied to predict emergency triage levels. We evaluated these models based on key performance metrics, including accuracy, F1-score, precision, and recall, to ensure the model's reliability and accuracy in identifying critical cases. Table 6 summarizes the performance metrics of all applied machine learning models:

Table 6: Performance metrics of all applied machine learning models

Model	Accuracy	F1-Score	Recall	Precision
ANN	72	68	75	62
RF	65	72	73	69
SVM	58	71	92	85
KNN	58	68	78	60
LR	65	69	68	70

First, Random Forest (RF): As an ensemble method that constructs multiple decision trees, RF was selected for its ability to reduce overfitting and improve classification accuracy through random sampling and feature importance. It performed with an accuracy of 65% and an F1-score of 71. Second, Artificial Neural Networks (ANNs): A deep learning model designed to capture complex, non-linear relationships between features. The ANN achieved 72% accuracy, with an F1-score of 68, a recall of 75, and a precision of 62. Third, Support Vector Machine (SVM): A model that excels in high-dimensional spaces, but it performed less effectively in this case with an accuracy of 58% and an F1-score of 71. Fourth, k-Nearest Neighbors (KNN): A simple, instance-based algorithm, KNN achieved an accuracy of 58%, with an F1-score of 68, performing similarly to SVM.

Finaly, Logistic Regression (LR): A baseline linear classifier, LR performed comparably to ANN and KNN, with an accuracy of 65% and an F1-score of 69. The Random Forest and ANN models emerged as the strongest performers, with ANN slightly outperforming Random Forest in terms of accuracy but requiring further tuning for optimal performance. The balanced performance across key metrics makes Random Forest a reliable model for classification in cloud-IoT health applications.

The results demonstrate that ANN and Random Forest are well-suited for cloud-IoT health monitoring applications, with ANN achieving the highest accuracy. However, Random Forest remains a strong candidate for its balance of accuracy, F1-score, and interpretability, making it a reliable option for triage predictions. The use of feature selection algorithms

further optimized the model's efficiency, ensuring that the most relevant features were used to predict emergency care needs.

4. Conclusions

This study demonstrates the potential of integrating IoT-enabled wearable devices and AI-driven machine learning models to improve healthcare outcomes for Hajj pilgrims. By continuously monitoring pilgrims' vital signs in real-time and utilizing advanced predictive algorithms, the proposed system offers timely alerts and proactive interventions, which can significantly reduce health risks during the pilgrimage. The integration of edge computing with cloud platforms ensures that large volumes of data are processed efficiently, allowing healthcare providers to make informed decisions based on real-time health data. Through feature selection and the application of machine learning models such as Random Forest and Artificial Neural Networks, the system accurately predicts emergency situations, enabling timely medical interventions. The results of this study suggest that leveraging IoT and AI technologies for healthcare during mass gatherings like Hajj can enhance the safety and well-being of pilgrims while reducing the burden on medical personnel.

5. Recommendations

Future work should focus on improving the scalability and reliability of the proposed system, especially when dealing with large-scale events like Hajj, where millions of people gather in concentrated locations. Additionally, efforts should be made to further refine the machine learning models through the use of larger, more diverse datasets to improve their accuracy in detecting a wider range of health conditions. It is also recommended to explore more advanced AI techniques such as deep learning and reinforcement learning to enhance the system's predictive capabilities. Furthermore, addressing ethical concerns related to data privacy and the secure transmission of sensitive health information is critical. Lastly, collaboration with healthcare providers and government agencies will be essential for the successful deployment and adoption of such systems in real-world scenarios, ensuring that the technology is effectively integrated into the broader healthcare infrastructure for pilgrims.

References

N. T, W. DMP, C. P. Artificial Intelligence - Enabled IoT for Health and Wellbeing Monitor ing. International Conference on Computing Communication and Networking Tec hnologies .

2. N. A, Turki A, Oumaima S, Muhammad U, Z. F, Nihal A, et al. Monitoring Acute Heart Failure Patients Using Internet-of-Things-Based Smart Monitoring System. Italian National Conference on Sensors [Internet]. Available from: https://www.mdpi.com/1424-8220/23/10/4580/pdf?version=1683687446

3. Bharat G, Parul C, Ruchira S, P. C. IoT based System Design for Human Health Monitoring for Covid -19 Outb reak. 2022 International Mobile and Embedded Technology Conference (MECON) .

4. Assistant, C. B. IoT based Health and Safety System for Manual Scavengers and Miners .

5. Mr. D, Mr. M, Mr. P. Health Monitoring System Using IOT Sensor. International Research Journal on Advanced Science Hub .

6. God I, Jagtap S, Suryavanshi C, Pawar B, Ghatage S, Salunkhe P. IoT Based Health Monitoring System. Int J Res Appl Sci Eng Technol [Internet]. 12(2):943–6. Available from: http://dx.doi.org/10.22214/ijraset.2024.58454

7. Metuge V, Valero M, Zhao L, Nino V, Claudio D. Preliminary Data Collection for Collaborative Emergency Department Crowd Management using Wearable Devices. In: 2022 IEEE International Conference on Digital Health (ICDH). IEEE; 2022. p. 34–6 .

8. Nino V, Claudio D, Schiel C, Bellows B. Coupling wearable devices and decision theory in the United States emergency departme nt triage process: A narrative review. Int J Environ Res Public Health. 2020;17(24):9561 .

9. D. R, S. H, Alexandre G, Wilhelm S, Benedikt W, Markus E. Towards automatic sensor-based triage for individual remote monitoring during mass casualty incidents. IEEE International Conference on Bioinformatics and Biomedicine .
10. Caitlin P, Titus J, U. G, G. N, T. H, Emilio A, et al. Wearable Bluetooth Triage Healthcare Monitoring System. Italian National Conference on Sensors [Internet]. Available from: https://www.mdpi.com/1424-8220/21/22/7586/pdf?version=1637051881
11. Rocío SS, J. GU, Luis AG, María CR, M. BMC, Almudena VS, et al. Machine learning methods applied to triage in emergency services: A sy stematic review. Int Emerg Nurs .
12. Henry M, Alvin N, J. N, Ggaliwango M. Interpretable Machine Learning-Based Triage For Decision Support in Em ergency Care. 2023 7th International Conference on Trends in Electronics and Informa tics (ICOEI) .
13. Choi SW, Ko T, Hong KJ, Kim KH. Machine Learning-Based Prediction of Korean Triage and Acuity Scale Le vel in Emergency Department Patients. Healthc Inform Res [Internet]. 25(4):305. Available from: http://dx.doi.org/10.4258/hir.2019.25.4.305
14. Huilin J, Haifeng M, Huimin L, Peiyi L, W. G, Huijing L, et al. Machine learning-based models to support decision-making in emergency department triage for patients with suspected cardiovascular disease. Int J Medical Informatics.

Enhancing Wayfinding Systems for Crowd Health and Safety in Makkah: Assessing Al-Aziziya and Al-Zahir Neighborhoods

Abdullah Saeed Karban

Department of Architecture, Umm Alqura University

*Corresponding author: E-mail (askarban@uqu.edu.sa)

تعزيز أنظمة الارشاد المكاني لتحقيق صحة وسلامة الحشود: تقييم حي العزيزية والزاهر بمكة المكرمة

عبدالله بن سعيد عيظة كربان

استاذ العمارة و التخطيط الحضري المساعد، جامعة ام القري

الملخص

تتناول هذه الدراسة دور أنظمة الإرشاد المكاني، بما في ذلك اللوحات الإرشادية والهوية الحضرية، على صحة وسلامة الحشود في الأحياء السكنية بمكة المكرمة خلال موسمي الحج والعمرة. حيث يعتمد ملايين الزوار على هذه الأنظمة للتنقل في مناطق غير مألوفة ومكتظة بالمستخدمين. ومع ذلك، فإن عدم اكتمال البنية التحتية، وضعف تواجد اللوحات الإرشادية، ومحدودية الدعم متعدد اللغات، والافتقار إلى علامات حضرية، قد يؤدي إلى عدم الوصول إلى الوجهات النهائية للمستخدمين أو الازدحام وازدياد المخاطر المتعلقة بالسلامة والأمان. حددت الدراسة وجود فجوة كبيرة في الدراسات التي تركز على أنظمة الإرشاد المكاني والوصولية على مستوى الأحياء في المدن ذات الكثافة السكانية العالية والتي تشهد ارتفاع في أعداد المستخدمين في المناطق غير المألوفة لديهم.

ولذلك، تم استخدام نهج مختلط، يجمع بين المسح الميداني وتقييم الوضع الراهن في كل من أحياء العزيزية والزاهر، بالإضافة إلى جمع البيانات الكمية من خلال الاستبانات الرقمية التي تجاوب معها 179 فردا. أظهرت النتائج أن أنظمة الإرشاد المكاني في مكة المكرمة غير الكافي قد أثر سلبًا على تدفق الحشود وسلامتها. خلصت الدراسة إلى أن تحسين رؤية اللوحات الإرشادية، وتعزيز الهوية الحضرية أمرا بالغ الأهمية للحد من التيه، وتخفيف الازدحام، وتحسين السلامة العامة في المناطق السكنية في مكة المكرمة خلال موسمي الحج والعمرة.

الكلمات الدالة: الإرشاد المكاني، مكة المكرمة، الأحياء، سلامة الحشود، ضيوف الرحمن، الحج والعمرة.

Abstract

This study examines the role of wayfinding systems, including signage and urban identity, in ensuring crowd health and safety in Makkah Al-Mukarramah's residential neighborhoods during peak pilgrimage seasons, such as Hajj and Umrah. Millions of Al-Rahman guests rely on these systems to navigate unfamiliar, densely populated areas. However, the current infrastructure is insufficient, with poor signage, limited multilingual support, and a lack of recognizable urban identity, leading to confusion, crowd congestion, and safety risks. The research identifies a significant gap in studies focused on neighborhood-level wayfinding in high-density religious cities.

To address this, a mixed-method approach was used, combining observation in Al-Aziziya and Al-Zahir neighborhoods with a survey of 179 pilgrims. Results show that inadequate wayfinding systems negatively affect crowd flow and safety. The study concludes that improving signage visibility, ensuring multilingual accessibility, and enhancing urban identity

are critical for reducing disorientation, easing crowd congestion, and improving overall safety in Makkah's residential areas during religious seasons.

Keywords: Wayfinding, Makkah, Neighborhoods, Crowed Safety, Pilgrims, Hajj and Umrah

1. Introduction

Wayfinding systems, which encompass various tools and strategies designed to help individuals navigate and orient themselves within physical spaces, play a critical role in urban environments (Alinaghi & Giannopoulos, 2024; Boumenir et al., 2010). In densely populated areas, such as the residential neighborhoods of Makkah Al-Mukarramah, these systems are essential for ensuring the efficient movement of pilgrims, especially during peak periods of Hajj and Umrah seasons. Effective wayfinding attributes, such as clear signage and strong urban identity markers, provide essential visual cues that help residents and visitors alike navigate unfamiliar or crowded spaces(Zhou & Ujang, 2024a). Signage offers clear direction, while urban identity, including distinctive architectural elements and spatial organization, helps create a sense of place and orientation within built environments (McCunn & Gifford, 2018; Passini, 1984).

Makkah's neighborhoods, particularly during Hajj and Umrah, become unfamiliar and challenging environments for millions of Al-Rahman guests. With over 1.8 million pilgrims attending Hajj annually and more than 26.85 million visiting for Umrah(Hajj Statistics, 2023; Umrah Statistics, 2023), the city's residential areas experience a massive influx of visitors who are often unfamiliar with the local context. Navigating narrow streets and densely built environments, combined with language barriers, can create significant disorientation for Al-Rahman guests. According to Scouts Guide, over 206,000 pilgrims were reported miss their destination or lost from their groups during previous Hajj season(Al-Rabiah, 2023). These conditions highlight the critical role that wayfinding systems play in maintaining crowd safety and ensuring smooth navigation at neighborhood level.

Insufficient wayfinding systems can exacerbate crowding and confusion, leading to safety risks such as overcrowding, stress, and delays in emergency response (Shiwakoti et al., 2023). On the other hand, well-placed signage and clear urban identity markers can significantly reduce the likelihood of such problems by enabling easier navigation and improving crowd management. Ensuring that residents and visitors alike can move safely and efficiently through these areas is not only a matter of convenience but also crucial to maintaining public health and safety.

The objective of this study was to explore the impact of wayfinding systems, particularly signage and urban identity, on the health and safety of crowds in residential neighborhoods of Makkah Al-Mukarramah. By focusing on how these systems function at the neighborhood level, this study aimed to identify key improvements that can enhance safety, reduce disorientation, and improve overall crowd management for both residents and the millions of Al-Rahman guests.

2. Literature Review

Wayfinding systems are an integral aspect of urban design, especially at the neighborhood level, where they facilitate crowed movement, enhance safety, and reduce the cognitive load of navigating complex environments. Research has shown that wayfinding system is a reflection of human's behavior. For example, urban environments impact uses' perception and cognition (J. Wu et al., 2024). The implementation of wayfinding systems involves the strategic use of signage, landmarks, and spatial identity to guide individuals through unfamiliar or densely populated spaces(Farr et al., 2012). In neighborhoods, wayfinding systems are crucial for improving the overall experience of both residents and visitors, particularly in urban areas with intricate layouts. However, there remains a significant gap in the research

regarding the effectiveness of wayfinding systems in high-density neighborhood, like Makkah that considered very significant urban environments for Muslims. This gap is particularly relevant given the unique spatial and crowd management challenges that Makkah faces, especially during Hajj and Umrah.

At the neighborhood level, wayfinding systems are essential for guiding people through local streets and pathways, reducing confusion, and ensuring smooth mobility (Askarizad et al., 2024). As Lynch (1960) mentioned, the ability of individuals to form a clear mental map of their surroundings is highly dependent on the environmental cues available to them, such as signage and landmarks (Lynch, 1960). Well-designed wayfinding systems allow people to navigate confidently through unfamiliar spaces, reducing crowed, stress and disorientation(Farr et al., 2012). This is especially important in neighborhoods, where streets can be narrower and less standardized compared to city centers, making navigation more challenging.

In Makkah, the importance of wayfinding systems is increased by the importance of providing great services to the millions of Al-Rahman guests. These pilgrims often come from diverse cultural and linguistic backgrounds, further complicating their ability to navigate Makkah's dense and complex neighborhoods. The densely built areas, wayfinding is critical for avoiding crowd congestion and ensuring the safety of pilgrims (Gazzawe & Albahar, 2024), particularly those unfamiliar with the local context. However, the existing literature lacks comprehensive studies that assess the wayfinding systems at neighborhood level specifically in the Holy city of Makkah during rituals seasons. This gap in research is significant because the high density and the uniqueness of religious context of Makkah make its neighborhood-level wayfinding challenges distinct from other cities.

The practice of wayfinding at the neighborhood level involves several core components including signage, landmarks, and urban identity elements that provide a sense of orientation for individuals (Farr et al., 2012; Zhou & Ujang, 2024b). Effective signage is one of the most common tools used in urban wayfinding. It must be clear, multilingual, and accessible to diverse populations, particularly in international cities like Makkah, where non-Arabic speaking pilgrims rely heavily on visual cues to navigate(Iftikhar, 2022). However, research indicates that existing wayfinding systems in Makkah's neighborhoods, particularly in areas surrounding the Holy Mosque, are often insufficient in providing clear direction for pilgrims (Alkharoubi, 2020a).

Another key practice in neighborhood wayfinding is the use of traditional urban identity, such as architectural features, public spaces, artificial and natural landmarks, to help people orient themselves. Lynch, 1960; Passini, 1984 emphasized that landmarks are highly effective in helping users form a cognitive map of their surroundings. In Makkah, major religious landmarks, such as the Holy Mosque and nearby towers, serve as vital wayfinding points. Also, Moaques at neighborhood level play the same role (Karban, 2020). However, in the residential neighborhoods further away from these landmarks, there is a gap in the availability of easily recognizable urban areas. This gap in the practice of wayfinding highlights a significant issue in Makkah's current wayfinding infrastructure: while central areas are well-served by prominent landmarks, residential neighborhoods—where pilgrims also need to navigate—are less equipped with these critical orientation tools.

While there have been numerous studies on the effectiveness of wayfinding systems in general, there is a notable lack of research focused on neighborhood-level wayfinding in high-density religious cities like Makkah and their impacts on crowed safety. Most of the existing research on wayfinding systems focuses on general urban environments, where challenges related to crowd density and cultural diversity are less pronounced than in cities like Makkah. For instance,

studies by Bhatt & Kolay, 2020; Boumenir et al., 2010 explore the impact of signage and landmarks on wayfinding, but do not address the unique needs of populations navigating religiously significant spaces where millions of visitors gather simultaneously.

In Makkah, the need for effective wayfinding systems is even more critical due to the significance of pilgrims during Hajj and Umrah. (Kadi et al., 2021; Khalid et al., 2024)highlighted that in peak pilgrimage seasons, the existing wayfinding infrastructure fails to accommodate the sheer volume of visitors and the linguistic diversity among pilgrims. This study gap underscores the need for more research on the design and implementation of neighborhood-level wayfinding systems in Makkah, to address the unique challenges faced by the city. Current research also lacks exploring the connection between inadequate wayfinding and crowd safety in these environments, despite the well-documented risks associated with overcrowding during Hajj and Umrah seasons.

Wayfinding systems not only improve navigation but also have a direct impact on crowd behavior and safety. In high-density environments, poor wayfinding can lead to confusion, congestion, and even accidents as people struggle to find their way (Baskaya et al., 2004). Raineri, 2015 found that in environments with inadequate signage, individuals tend to cluster in confusion, leading to bottlenecks and potentially dangerous crowd. This is particularly concerning in a city like Makkah, where crowd management is a critical safety issue, especially during Hajj, when millions of people are moving through the same spaces at the same time.

In Makkah's neighborhoods, poor wayfinding systems contribute not only to disorientation but also to increased stress and anxiety among pilgrims, particularly those who are unfamiliar with the city and culture. The lack of clear directional signage caused pilgrims to get lost frequently, resulting in delays, crowding, and, in some cases, safety(Al-Ghamdi et al., 2021).

Despite these findings, there remains a significant gap in the literature regarding how neighborhood-level wayfinding systems in Makkah specifically affect crowd behavior and safety. This gap points to the need for further research to understand how improved wayfinding infrastructure can mitigate safety and enrich pilgrimage experience in Makkah.

The literature review underscores the critical role of wayfinding systems at the neighborhood level, particularly in high-density urban environments like Makkah. While several studies have explored the importance of signage, landmarks, and urban identity for effective navigation, there remains a significant gap in research focused on neighborhood-level wayfinding systems in Makkah during Hajj and Umrah seasons. Addressing these gaps is essential for enhancing crowd management, improving safety, and enriching pilgrimage experience for millions of Al-Rahman guests. To fill this gap, it is necessary to not only analyze existing literature but also gather primary data from users directly affected by the neighborhood wayfinding systems.

3. Methodology

This study employs a mixed-method approach, combining both qualitative and quantitative data collection to comprehensively assess the wayfinding systems in the residential neighborhoods of Makkah. The chosen method allowed for a thorough investigation of not only the current wayfinding infrastructure in the Al-Aziziya and Al-Zahir neighborhoods but also an in-depth exploration of the experiences and behaviors of Al-Rahman guests during religious seasons. The first phase of the study involved a site visit and observational study conducted during the holy month of Ramadan 1445H. This period is particularly significant due to the high density of pilgrims and visitors, which puts

considerable pressure on the neighborhood wayfinding infrastructure. As show in figure 1, the observational study focused on the two key neighborhoods—Al-Aziziya and Al-Zahir —both of which experience a high density of Al-Rahman guests.

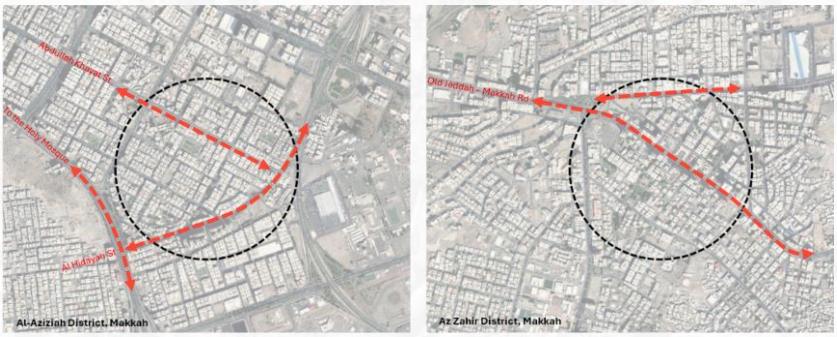


Figure 1: Study Area, Al-Aziziya and the Al-Zahir district, Makkah

These pilgrimage housing neighborhoods were selected through the observation of the lack of wayfinding components such as signage system, marked pathways, Landmarks, Lighting, pedestrian Sidewalks, Transit Stops, Local Guides and Urban identity. As show in figure 2, the available wayfinding system such as signage are not oriented to pedestrians, lack of pedestrian sidewalks and there was shortage of the urban identity of both areas. Therefore, this study aims to assess the wayfinding system through users' perceptions.

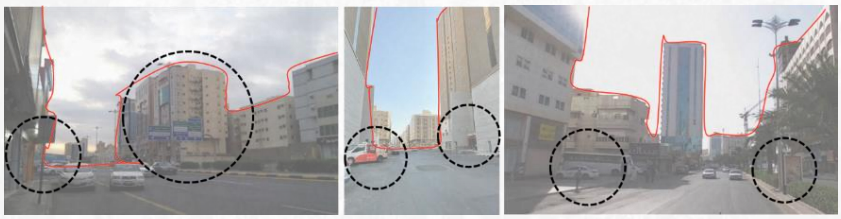


Figure 2: Study Area, Al-Aziziya and the Al-Zahir neighborhoods, Makkah

During the site visit, direct observations were made to evaluate the physical placement, clarity, and availability of signage. The observation period provided qualitative insights into the operational efficiency of wayfinding systems under real-life conditions as shown in figures 3.

Figure 3: The lack and informality of wayfinding system at Al-Aziziya Neighborhood

The analyzed observation of Al-Aziziya neighborhood reveals a significant deficiency in pedestrian-oriented wayfinding systems. The streets are visibly congested, with limited or poorly placed signage that does not cater to the needs of pedestrians navigating these routes. The absence of marked pathways further exacerbates the challenge, making it difficult for individuals, especially first-time visitors, to orient themselves effectively. The lack of distinct urban identity markers and clear directional cues contributes to an environment where confusion and disorientation are common. This visual evidence aligns with observations that the current infrastructure fails to support efficient pedestrian movement,

thereby posing potential safety and congestion risks during peak periods such as Ramadan and Hajj. Without effective wayfinding systems, crowd health can be compromised due to increased stress and anxiety, and the potential for accidents or bottlenecks rises, making emergency responses slower and more difficult.

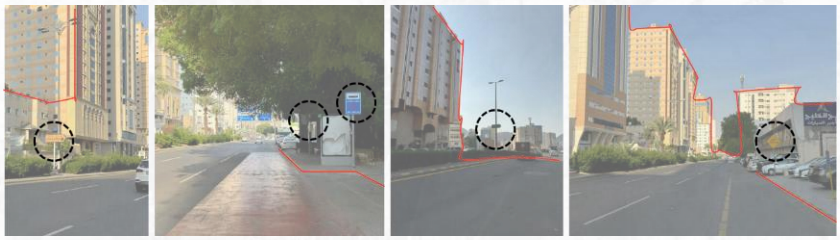


Figure 4: The lack and informality of wayfinding system at Al-Aziziya Neighborhood

Similarly, figure 4 illustrates the Al-Zahir neighborhood, emphasizing its streets that lack dedicated pedestrian sidewalks and an evident shortage of wayfinding tools. The visual points out the absence of clear landmarks or signage to aid visitors in navigating, revealing a significant shortfall in urban planning efforts centered on wayfinding. The inadequate lighting and poorly defined transit stops further exacerbate the challenge, creating navigational difficulties, especially for non-local pilgrims who are unfamiliar with the area. This assessment aligns with the observational findings that highlight how the absence of comprehensive wayfinding systems can hinder efficient movement and elevate stress among residents and visitors. The implications for crowd health and safety are considerable: without sufficient wayfinding infrastructure, individuals are at higher risk of crowding, heightened anxiety, and potential physical injuries as they attempt to move through chaotic spaces. Moreover, during emergency situations, the lack of clear guidance can severely delay evacuation efforts and compromise overall safety, posing significant risks to public well-being.

The second phase of data collection took place during Thul-Qaeda 1445H, utilizing a survey-based questionnaire to gather quantitative data from Al-Rahman guests who stayed or navigate through Al-Aziziya or Al-Zahir neighborhood. The questionnaire was designed in three sections including demographic information, evaluation of existing wayfinding system and elicit the perception of the respondents regarding their psychological feeling during crowed, which help to provide detailed information about the respondents' experiences with existing wayfinding systems, including their ease of use, accessibility, and the role these systems played in facilitating movement through crowded areas. The instrument also contained two specific questions aimed at assessing the ease of navigation and the potential for disorientation. These questions were: "Did you feel difficulty reaching your destination"?, and "Did you miss your orientation during this trip"?

The survey included both closed and open-ended questions to assess key variables such as the visibility of signage, the accuracy of directions provided, and respondents' overall satisfaction with the wayfinding tools. The overlooked the impact of language, education level, and familiarity with the neighborhood, but these factors could influence the ease of navigation. The questionnaire was distributed to a representative sample of Umrah performers and pilgrims mainly to who speaks Arabic or English, to ensure a comprehensive overview of user experiences. Thus, the study sample comprised a total of 179 respondents who participated in the quantitative survey. These participants were Al-Rahman guests stayed at Al-Aziziya and Al-Zahir neighborhoods in Makkah, both of which experience high pedestrian and vehicular traffic during Hajja and Umrah seasons. The sample size of 179 respondents for this study was chosen to balance practical data collection constraints and the goal of obtaining meaningful insights into the wayfinding experiences of pilgrims in the high-density neighborhoods of Makkah. While larger samples could provide more

statistically robust conclusions, this size still offers sufficient data to identify trends, perceptions, and common challenges faced by Al-Rahman guests in navigating the Al-Aziziya and Al-Zahir neighborhoods. According to (Memon et al., 2020)in "Sample Size for Survey Research: Review and Recommendations," while large samples can enhance reliability, smaller samples, when carefully chosen, can be just as meaningful, with 150 and above deemed sufficient for reliable insights. The study's sample size is justifiable given the unique population and context during Hajj and Umrah seasons. Collecting data during these peak periods is challenging due to the influx of visitors, limited respondent access, and time constraints. Although not expansive, this sample allows for meaningful cross-sectional analysis and comparisons, further enriched by qualitative observations. Future research can expand these findings with larger or longitudinal studies for broader generalizability, but the current sample provides valuable initial evidence on wayfinding system effectiveness and areas for improvement. The demographic analysis of the respondents provides important insights into their background, which can help contextualize their interactions with the wayfinding systems as shown in table 1. Itis important as it provides essential context for understanding the characteristics and backgrounds of the study participants, which can influence their interactions and experiences with wayfinding systems. By analyzing factors such as age, gender, educational level, and language, researchers can identify specific needs and challenges faced by different groups. This insight helps tailor wayfinding solutions that are inclusive and effective, ensuring they address the diverse requirements of users. Additionally, demographic analysis aids in interpreting the study results more accurately and making targeted recommendations for improvements in urban navigation systems.

Table 1: Demographic Analysis

		Frequency	Percent	Valid Percent	Cumulative Percent
Gender	Male	114	63.7	63.7	63.7
	Female	65	36.3	36.3	100.0
	Total	179	100.0	100.0	
Age	18 - 25	70	39.1	39.1	39.1
	26 - 40	82	45.8	45.8	84.9
	41 - 60	27	15.1	15.1	100.0
	Total	179	100.0	100.0	
Marital status	Single	49	27.4	27.4	27.4
	Married	127	70.9	70.9	98.3
	Widowed	3	1.7	1.7	100.0
	Total	179	100.0	100.0	
Educational level	High School or Less	19	10.6	10.6	10.6
	Diploma	53	29.6	29.6	40.2
	Graduate	85	47.5	47.5	87.7
	Postgraduate	22	12.3	12.3	100.0
	Total	179	100.0	100.0	
Language	Arabic	95	53.1	53.1	53.1
	English	32	17.9	17.9	70.9
	Urdu	17	9.5	9.5	80.4
	Bangla	9	5.0	5.0	85.5
	Other	26	14.5	14.5	100.0
	Total	179	100.0	100.0	
Neighborhood of Stay	Al-Aziziya	121	67.6	67.6	67.6
	Al-Zahir	58	32.4	32.4	100.0
	Total	179	100.0	100.0	

Table 1 and the following figure show, gender distribution in the study indicates that the majority of participants were male, comprising 63.7% (114 participants), while females made up 36.3% (65 participants). This distribution reflects the demographics of individuals navigating the residential neighborhoods of Makkah, particularly during pilgrimage seasons. Understanding the gender balance among respondents is crucial, as it can provide insights into differing experiences and challenges faced by men and women in relation to wayfinding and navigating crowded environments. However, the study did not find significant differences between men's and women's perceptions of the wayfinding systems. This suggests that both genders share similar experiences and challenges when it comes to navigation, highlighting the need for inclusive improvements that benefit all users.

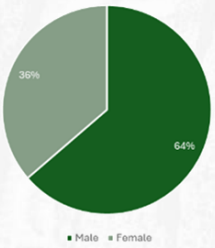


Figure 5: Respondents Gender Distribution for both areas

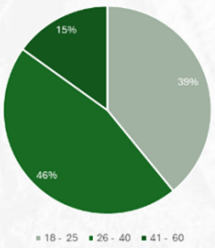


Figure 6: Respondents Age Distribution for both areas

The age distribution of the respondents was relatively balanced, with the majority (45.8%) falling within the 26-40 age group, followed by 39.1% in the 18-25 age group. A smaller portion (15.1%) of respondents were between 41-60 years of age as shown in figure 6. This demographic distribution indicates that the majority of participants are of working age, which may influence their ability to interact with more complex digital wayfinding systems.

Regarding the marital status of respondents, figure 7 illustrates that most of the respondents (70.9%) were married, 27.4% were single, and 1.7% were widowed. The predominance of married individuals in the sample could suggest that family units are a key demographic navigating the residential neighborhoods of Makkah, which may present unique navigation needs when moving in groups.

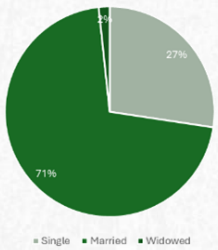


Figure 7: Respondents Marital status Distribution

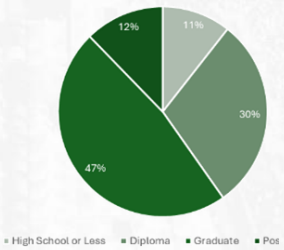


Figure 8: Respondents Educational level Distribution

The educational background of the respondents as shown in figure 8 varied, with 47.5% being graduates, 29.6% holding diplomas, 12.3% having postgraduate qualifications, and 10.6% possessing a high school education or less. This suggests that most respondents are well-educated, potentially facilitating their interaction with technologically advanced wayfinding systems, as higher education levels often correlate with better comprehension of complex navigation tools like mobile apps or digital signage. However, the presence of respondents with lower education levels highlights the need for wayfinding systems to be intuitive and user-friendly to cater to everyone. Clear visual cues, symbols, and simple instructions are essential to ensure that individuals with limited literacy or technological familiarity can navigate

effectively. If wayfinding systems are not accessible to all education levels, it can lead to confusion and crowding, with less-educated individuals requiring more time to orient themselves, potentially causing delays and congestion. Therefore, designing inclusive wayfinding solutions helps promote smooth movement, reduce cognitive load, and enhance crowd safety and efficiency.

As show in table 1 and in figure 9 the majority of respondents (53.1%) speak Arabic, reflecting Makkah's location in Saudi Arabia, where Arabic is the official language. Many respondents work or study in Arabic-speaking cities such as international students at Saudi Universities, and the religious significance of Arabic in Islam further strengthens its dominance. Additionally, a portion of respondents speaks English (17.9%), Urdu (9.5%), Bangla (5.0%), and other languages (14.5%), reflecting the city's international population of workers, students, and pilgrims. This diversity highlights the importance of multilingual wayfinding systems for improving accessibility and safety in Makkah's crowded environments.

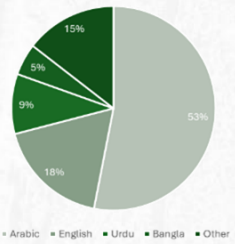


Figure 9: Respondents Marital status Distribution

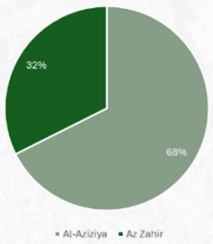


Figure 10: Respondents Educational level Distribution

Identifying respondents' neighborhoods is crucial for understanding the specific challenges and experiences associated with navigating different areas. Each neighborhood in Makkah may have unique characteristics, infrastructure issues, or crowd dynamics that impact the effectiveness of wayfinding systems. By distinguishing where respondents are staying, researchers can pinpoint which areas need more targeted interventions or improvements to better manage crowd flow and enhance navigation. In this study, acknowledging respondents' neighborhoods allows for a more nuanced analysis of wayfinding system effectiveness and highlights disparities between different locations. As shown in figure 10, a significant proportion of the respondents (67.6%) stayed in Al-Aziziya, while 32.4% were from Al-Zahir.

This concentration in Al-Aziziya suggests that this neighborhood may require more focused attention to improve wayfinding systems, especially during pilgrimage seasons when the crowd density is at its peak. Addressing the specific needs of high-traffic areas like Al-Aziziya can help ensure that navigation support is optimized for the largest number of users, thus improving overall crowd management and safety.

The reliability test shows that the survey is consistent and dependable. As shown in table 2, the factor "Evaluation of Wayfinding Systems" (7 items), the Cronbach's Alpha value is 0.906, and for "Measuring the Psychological Impact on Crowd Movement" (8 items), it is 0.878 . These high values mean that the questions in both sections worked well together to measure what they were supposed to. Reliability values above 0.8 are considered good, which helps ensure that the data collected is accurate and useful for understanding how wayfinding systems can improve crowd safety in Makkah(De Vera et al., 2010).

Table 2: Reliability Statistics

Scale	Cronbach Alpha	No of Items
Evaluation of Wayfinding system	.906	7
Measuring the psychological impact on Crowed Movement	.878	8

In the Data Analysis, both descriptive statistics and Cross-tabulation were used to summarize and explore the data using $SPSS_{21}$ software. Cross-tabulation allowed for the examination of relationships between demographic variables, such as age and gender, and respondents' perceptions of wayfinding systems(Pallant, 2013). Additionally, the Chi-square test was applied in SPSS to determine whether there were statistically significant associations between these variables and user experiences with the wayfinding systems. These tests provided valuable insights into how different groups interacted with the systems and the impact on their navigation experience. The results of these analyses provide a deeper understanding of how different demographic groups experience and interact with the wayfinding systems in Makkah. By examining the relationships between variables, the key patterns can be identified and significant associations that influence crowd navigation and safety. The next section provides detailed findings from the descriptive statistics, cross-tabulations, and chi-square tests are presented, offering insights into the effectiveness and challenges of the current wayfinding systems.

4. Results and Discussion

The Results and Discussion section presents the key findings from the data analysis, offering a comprehensive overview of how respondents interacted with the wayfinding systems in Makkah's residential neighborhoods. This section also discusses how these results align with existing research and identifies potential areas for improvement. As display in table 3, there were two questions asked to assess the effectiveness of the wayfinding systems from the users' perspectives: "Did you feel difficulty reaching your destination?" and "Did you miss your orientation during this trip?" These questions aimed to capture the respondents' direct experiences with navigation and disorientation challenges while navigating Makkah's residential neighborhoods.

Table 3: Descriptive Statistics of the respondents' feeling Difficulty reaching their destination

Did you feel difficulty reaching your destination?	Frequency	Percent	Valid Percent	Cumulative Percent
No	129	72.1	72.1	72.1
Yes	50	27.9	27.9	100.0
Total	179	100.0	100.0	

According to previous table, the respondents who did not feel difficulties reaching their destination represents, the majority of respondents (72.1%), while 27.9% reported having difficulty. This high percentage indicates that, for most, the signage, pathways, and landmarks provided sufficient guidance to navigate the area without major confusion or delays. It reflects positively on the existing system's ability to support clear and efficient movement, especially during crowded times.

However, the fact that 27.9% of respondents still encountered difficulties highlights that there is a significant portion of the population facing challenges with the system. This is a substantial number, indicating that while the system works for the majority, nearly a third of users experience obstacles in navigation. This could be due to factors such as unclear or insufficient signage in certain areas, a lack of multilingual support, or the complexity of the urban environment, especially for visitors unfamiliar with the area. Similar studies have shown that even in well-developed urban environments, certain user groups—particularly first-time visitors, non-native speakers, and the elderly—often struggle with navigation,

underscoring the need for continuous improvements in wayfinding systems (Alkharoubi, 2020b).Therefore, this 27.9% serves as a critical indicator that further adjustments are necessary to ensure inclusivity and ease of navigation for all users, including those who may be less familiar with the local context.

On the other hand, the second question in the survey focused on whether respondents missed their orientation during the trip, aiming to understand the causes of potential disorientation while navigating Makkah's residential neighborhoods. This question was particularly important for identifying specific challenges faced by Al-Rahman guests, such as language barriers or uniform building designs, that could delay effective navigation.

Table 4: Descriptive Statistics of the respondents' reasons for missed orientation

Did you miss you orientation during this trip?	Frequency	Percent	Valid Percent	Cumulative Percent
No	124	69.3	69.3	69.3
Yes, because buildings look the same	5	2.8	2.8	72.1
Yes, because the places are not defined on Google Maps in my language	13	7.3	7.3	79.3
Yes, because there are no guides speaking my language	19	10.6	10.6	89.9
Yes, because there are no sig1ge in my language	18	10.1	10.1	100.0
Total	179	100.0	100.0	

In table 4, the data indicates that 69.3% of respondents did not miss their orientation during the trip, which is compliment to previous question, suggesting that the majority of respondents were able to maintain their sense of direction and navigate the residential neighborhoods effectively. This result highlights the general adequacy of the current wayfinding systems for most respondents. This finding raise the question mark about having wayfinding system, whereas during the site visit and observational study approved that there was a lack of wayfinding components in the study area. However, the fact that 30.7% of respondents did miss their orientation reveals important challenges that certain groups face when navigating the area as shown in figure 11.

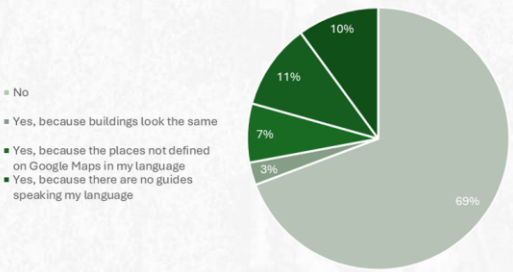


Figure 11 Respondntes perception on missing orientation during the trip

Several factors contributed to the difficulties experienced by those who lost their orientation. A small portion (2.8%) of respondents cited the uniformity of building designs as a key issue. In areas where buildings look the same, users may struggle to distinguish landmarks, which plays a critical role in wayfinding. This is consistent with research that emphasizes the need for unique architectural features to aid navigation in urban environments (Iftikhar, 2022; Passini, 1984). Language barriers also emerged as a significant factor, with 7.3% of respondents attributing their disorientation to the lack of place names on Google Maps in their language. Similarly, 10.6% reported difficulty due to the absence of guides speaking their language, while 10.1% cited the absence of signage in their language as a contributing factor. Together, these responses point to the need for enhanced multilingual and universal samples support, both in physical signage and digital navigation tools. As Makkah attracts an international population, particularly during Hajj and umrah

seasons, ensuring that wayfinding systems are accessible in multiple languages is crucial for reducing confusion and improving user experience (Alkharoubi, 2020b; Khalid et al., 2024).

These findings underscore the importance of addressing both urban design issues and linguistic accessibility to ensure that the wayfinding systems serve the diverse needs of Dhoyof Al Rahman. The first objective of this study aimed to assess the effectiveness of the current wayfinding systems in Makkah. The analysis of Al-Rahman guests' experiences provides valuable insights into how well these systems perform in guiding visitors through crowded areas, with a focus on accessibility, signage clarity, and overall ease of navigation. Table 4 shows, the current wayfinding systems in Makkah's residential neighborhoods are perceived as effective, particularly during peak religious seasons, aligning well with the first study objective. High average scores for key variables such as availability of signage systems (Mean = 4.22, SD = 1.16), marked pathways (Mean = 4.25, SD = 1.03), and landmarks (Mean = 4.17, SD = 1.15) indicate that the majority of respondents found the systems both clear and reliable. This supports findings from recent research that emphasize the critical role of signage and pathways in ensuring smooth navigation in crowded urban settings (Zhou & Ujang, 2024b). The consistency of these responses, as shown by low standard deviations, suggests that the effectiveness of wayfinding systems is uniformly experienced across different user groups, reinforcing their importance during high-traffic periods such as religious events.

Table 4: Descriptive Statistics of Wayfinding System Components in Makkah's Residential Neighborhoods

Indicator	N	Minimum	Maximum	Mean	Std. Dev
Availability of signage system	179	1.00	5.00	4.2235	1.15890
Availability of Marked pathways	179	1.00	5.00	4.2458	1.03094
Availability of Landmarks	179	1.00	5.00	4.1732	1.15543
Availability of Lighting	179	1.00	5.00	4.4916	.74478
Availability of pedestrian Sidewalks	179	1.00	5.00	4.2905	.95663
Availability of Transit Stops	179	1.00	5.00	4.2905	.99689
Availability of Local Guides	179	1.00	5.00	3.8827	1.29939
Availability of Urban identity	179	1.00	5.00	4.0168	1.19679
Valid N (listwise)	179				

Regarding to respondents' perceptions of various components of the wayfinding systems in Al-Aziziya and Al-Zahir neighborhoods, table 5 presents the majority of respondents rated signage systems positively, with 56.4% finding the signage effective, which suggests that it plays a crucial role in guiding individuals through busy areas. However, 7.8% of respondents rated the signage as poor, indicating that improvements are still needed, particularly in visibility and placement. Clear and consistent signage is essential for reducing confusion and ensuring smooth navigation, as supported by research on urban environments (K.-C. Wu & Wang, 2017).

Table 5: Perceptions of the Availability of Wayfinding System Components

Indicator		NA	Useless	Poor	Medium	Good	Total
Availability of signage system	Frequency	13	4	14	47	101	179
	Percent	7.3	2.2	7.8	26.3	56.4	100
Availability of Marked pathways	Frequency	8	6	12	61	92	179
	Percent	4.5	3.4	6.7	34.1	51.4	100
Availability of Landmarks	Frequency	13	3	19	49	95	179
	Percent	7.3	1.7	10.6	27.4	53.1	100
Availability of Lighting	Frequency	2	0	15	53	109	179
	Percent	1.1	0	8.4	29.6	60.9	100
Availability of pedestrian Sidewalks	Frequency	5	4	21	53	96	179
	Percent	2.8	2.2	11.7	29.6	53.6	100

Availability of Transit Stops	Frequency	6	5	19	50	99	179
	Percent	3.4	2.8	10.6	27.9	55.3	100
Availability of Local Guides	Frequency	21	3	27	53	75	179
	Percent	11.7	1.7	15.1	29.6	41.9	100
Availability of Urban identity	Frequency	15	5	21	59	79	179
	Percent	8.4	2.8	11.7	33	44.1	100

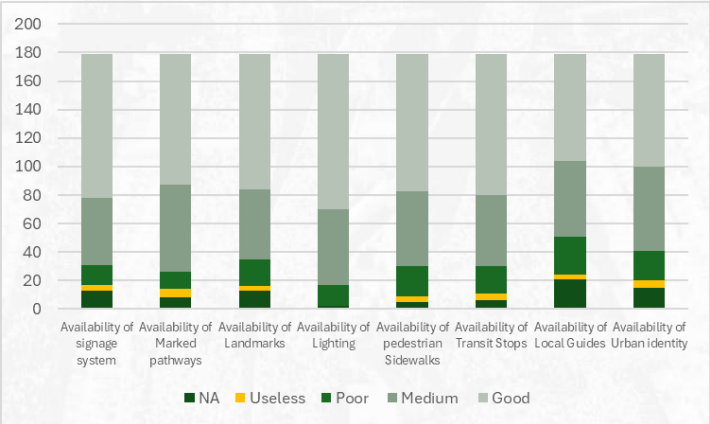


Figure12 Perceptions of the Availability of Wayfinding System Components

Similarly, 51.4% of respondents found marked pathways to be good, but 6.7% rated them poorly. Well-maintained pathways are vital for directing foot traffic, especially during busy times like Hajj, but the variability in quality highlights the need for more consistent infrastructure. Lighting was also positively received, with 60.9% rating it as good. However, 8.4% rated it as poor, indicating that some neighborhoods may require better illumination, especially to improve nighttime navigation. Addressing these issues is important to enhance overall safety and reduce anxiety when navigating unfamiliar areas (Phillips et al., 2013)

Pedestrian sidewalks and transit stops were generally seen as adequate, with 53.6% and 55.3% of respondents rating them positively. Yet, 11.7% found sidewalks inadequate, and 10.6% rated transit stops poorly, suggesting that while these systems serve most users, there are gaps in infrastructure that could affect pedestrian safety and accessibility. Local guides and urban identity markers, rated as good by 41.9% and 44.1% of respondents respectively, were viewed less favorably. This suggests that more efforts are needed to improve the availability of well-trained guides and integrate culturally significant landmarks that help orient visitors, particularly international pilgrims unfamiliar with the area (Karban, 2020; Zhou & Ujang, 2024b).

To enhance the effectiveness of these systems, several improvements are suggested. First, enhancing signage visibility and consistency across all neighborhoods will ensure that both residents and visitors can navigate effectively. Second, upgrading pedestrian sidewalks and transit infrastructure can provide a safer and more accessible environment, particularly during crowded events like Hajj and Umrah. Additionally, increasing the availability of samples and multilingual local guides will improve assistance for international visitors. Finally, investing in urban identity markers by introducing more culturally significant landmarks will improve orientation and enhance the overall wayfinding experience in Makkah's neighborhoods. In conclusion, the findings suggest that while the current wayfinding systems in Makkah's residential neighborhoods are generally effective, particularly in terms of signage, marked pathways, and lighting, there are still areas for improvement. Enhancing visibility and consistency in signage and pathways, improving

sidewalk infrastructure, and addressing the inadequacies in transit stops and local guides will further enhance user experiences. Additionally, strengthening the urban identity with more recognizable cultural landmarks could help visitors better orient themselves, ultimately improving overall navigation and safety.

The second objective of this study explores how the current wayfinding systems in Makkah's neighborhoods impact crowd behavior and safety. Wayfinding systems, including signage, landmarks, and urban identity, play a critical role in managing the movement of large crowds, particularly during Hajj. The effectiveness of these systems not only determines the flow and efficiency of crowd movement but also influences the psychological well-being of individuals navigating unfamiliar environments. By examining the emotional and behavioral responses to disorientation, as well as preferences for navigation tools, this section assesses how well the wayfinding systems are facilitating safe and orderly crowd behavior. In table 6, which focuses on evaluating how signage and urban identity markers influence crowd behavior and safety, the data reveal moderate levels of anxiety among respondents, with scores such as feeling upset and anxious (Mean = 3.80, SD = 1.25).

Table 6: Descriptive Statistics Psychological Impact Related to Navigation in Crowded Areas

Indicator	N	Minimum	Maximum	Mean	Std. Dev
feeling upset and anxious	179	1.00	5.00	3.7989	1.24693
feeling afraid when I get lost	179	1.00	5.00	3.5866	1.27950
feeling embarrassed to ask others	179	1.00	5.00	3.3631	1.27948
Guide does not speak my language	179	1.00	5.00	3.4078	1.23895
It is best to use signage	179	1.00	5.00	4.1676	.99711
I prefer asking the guides	179	1.00	5.00	3.9609	1.07245
I prefer using Google Maps	179	1.00	5.00	4.2123	.98851
I feel comfortable when neighborhood has wayfinding	179	1.00	5.00	4.3631	.99830
Valid N (listwise)	179				

Figure 13 Psychological Impact Related to Navigation in Crowded Areas

This suggests that while the systems are largely effective, there is still a level of psychological stress associated with navigating through unfamiliar environments, especially during peak times. The importance of clear and accessible wayfinding systems in reducing confusion and anxiety is supported by studies that highlight the need for visible and easily understood signage to promote crowd safety and well-being (Zhou & Ujang, 2024b).

Also, the respondents indicate that, the preference for both signage (Mean = 4.17, SD = 0.99) and Google Maps (Mean = 4.21, SD = 0.99) suggests that a hybrid system combining physical and digital navigation tools could significantly improve user experience. This approach is in line with recent findings that advocate for the integration of digital tools like Google

Maps with traditional signage to optimize navigation and reduce stress in complex urban environments (Tahir & Krogstie, 2023). Enhancing the visibility of signage, particularly during peak religious seasons, and ensuring that digital tools are readily accessible would help to further improve crowd management and alleviate the remaining anxiety felt by users.

The emotional impact of disorientation in Makkah's crowded neighborhoods is significant, with 68.2% of respondents feeling upset and anxious when lost. Emotional stress caused by disorientation can lead to irrational decisions and erratic movement, which further complicates crowd control in high-density environments. During events like Hajj, such behaviors can create dangerous situations, where confusion leads to overcrowding and potential safety risks. Clear and accessible wayfinding systems can mitigate these feelings of stress, promoting smoother navigation and better crowd management.

Table 7: Impact of Wayfinding Systems on Crowd Behavior and Safety

Indicator		Strongly Disagree	Disagree	Average	Agree	Strongly Agree	Total
feeling upset and anxious	Frequency	13	19	25	56	66	179
	Percent	7.3	10.6	14	31.3	36.9	100
feeling afraid when I get lost	Frequency	14	27	33	50	55	179
	Percent	7.8	15.1	18.4	27.9	30.7	100
feeling embarrassed to ask others	Frequency	18	29	44	46	42	179
	Percent	10.1	16.2	24.6	25.7	23.5	100
feeling comfortable with clear wayfinding	Frequency	6	8	8	50	107	179
	Percent	3.4	4.5	4.5	27.9	59.8	100
feeling upset when guide does not speak my language	Frequency	16	26	47	49	41	179
	Percent	8.9	14.5	26.3	27.4	22.9	100

As displayed in table 7, The fear experienced by 58.6% of respondents when lost also highlights the importance of reliable wayfinding tools. Research by (Boumenir et al., 2010)confirms that fear in unfamiliar environments can cause individuals to act unpredictably, which can disturb the flow of the crowd and increase the risk of accidents. Reducing this fear through effective signage and landmarks can help maintain a calm and orderly environment, which is crucial during large gatherings such as pilgrimages.

Furthermore, 49.2% of respondents felt embarrassed to ask for help, which may prevent them from seeking assistance when lost. This reluctance, combined with feelings of anxiety and fear, suggests that wayfinding systems should be designed to minimize the need for personal interaction and reliance on guides. A well-placed, multilingual signage can help reduce the burden on individuals to ask for directions, thus improving navigation experiences for international visitors who may already be uncomfortable or unfamiliar with the area.

Language barriers remain a significant factor, with 50.3% of respondents citing them as a cause of disorientation. Makkah, as a hub for international pilgrims, sees visitors from a vast array of linguistic backgrounds. The lack of multilingual support in signage or guides increases the likelihood of confusion and disorientation. According to Iftikhar, 2022, providing multilingual signage is crucial in large, multicultural cities to facilitate movement and improve user experience. Without such accommodations, crowd management becomes more difficult, and the likelihood of accidents or disruptions increases.

After that the Preferences were elicited for improving wayfinding tools and their role in crowd management as show in table 8. The overwhelming preference for signage, with 82.7% of respondents indicating that they prefer to rely on it for navigation, underscores the critical role of clear, visible signage in maintaining effective crowd control. Emphasizes that

in high-density areas as mentioned before (K.-C. Wu & Wang, 2017), must not only be frequent but also easily understood and visible from a distance to ensure that individuals can quickly orient themselves. The findings suggest that well-placed signage in Makkah's neighborhoods plays a key role in guiding both residents and pilgrims safely through crowded environments.

Table 8: Users Preferences of Using Wayfinding Systems

Indicator		Strongly Disagree	Disagree	Average	Agree	Strongly Agree	Total
It is best to use signage	Frequency	7	5	19	68	80	179
	Percent	3.9	2.8	10.6	38	44.7	100
I prefer asking the guides	Frequency	5	14	34	56	70	179
	Percent	2.8	7.8	19	31.3	39.1	100
I prefer using Google Maps	Frequency	6	5	21	60	87	179
	Percent	3.4	2.8	11.7	33.5	48.6	100

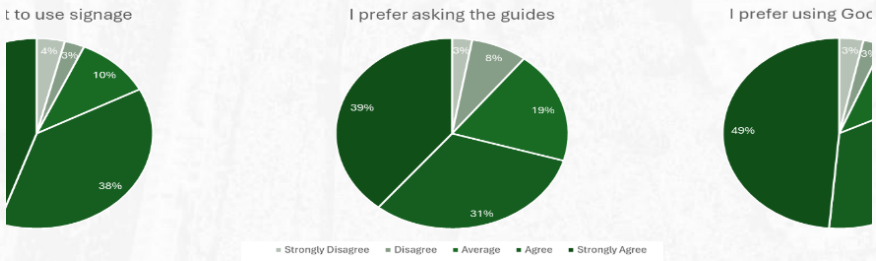


Figure 14 Users Preferences of Using Wayfinding Systems

As shown in table 8 and figure 14, the reliance on local guides also remains strong, with 70.4% of respondents preferring to ask guides for directions. Despite advancements in digital tools, human interaction continues to be an important aspect of navigation. Well-trained local guides can provide personalized assistance, especially when digital systems fail due to connectivity issues or language barriers. According to Alkharoubi, 2020, local guides are essential in large-scale events like Hajj, where many pilgrims may not be familiar with the city's layout or language. By increasing the availability of multilingual and well-trained guides, navigation can become smoother, and visitors will feel more supported in their journeys.

At the same time, 82.1% of respondents showed a strong preference for using Google Maps, reflecting the growing reliance on technology for wayfinding. Digital tools offer the advantage of real-time updates and GPS tracking, which can be particularly helpful in dynamic, crowded environments. However, as Tahir & Krogstie, 2023 notes, these tools should complement physical wayfinding systems, as internet connectivity can be unreliable in certain areas. Ensuring that signage and landmarks are in place as a backup can help mitigate potential navigation issues caused by technological disruptions.

Lastly, the high percentage of respondents (87.7%) who reported feeling comfortable when wayfinding systems were present highlights the importance of these systems in reducing stress and promoting a sense of safety. Effective wayfinding fosters confidence, allowing individuals to navigate crowded spaces without fear or confusion. Alkharoubi, 2020 argues that well-implemented wayfinding systems contribute to a more organized crowd flow, which is crucial for maintaining order and safety in large gatherings.

5. Conclusions

This study highlights the critical role of wayfinding systems in ensuring the health and safety of crowds in the residential neighborhoods of Makkah Al-Mukarramah, particularly during Hajj and Umrah. The findings reveal that while a significant portion of respondents reported adequate navigation support, a notable percentage still faced challenges due to insufficient signage, language barriers, and uniform building designs.

The research underscores the urgent need for enhancements in the wayfinding infrastructure, such as improving signage visibility, increasing multilingual support, and incorporating distinctive urban identity markers. These improvements are essential not only for reducing disorientation and crowd congestion but also for enhancing the overall experience for millions of pilgrims who navigate these densely populated areas.

In conclusion, addressing the gaps identified in this study is crucial for fostering a safer and more efficient environment for both residents and visitors. Future research should focus on continuous evaluation of wayfinding systems to adapt to the evolving needs of Makkah's diverse population, ensuring that the city can accommodate the influx of pilgrims while maintaining public health and safety. By prioritizing these enhancements, Makkah can improve crowd management and provide a more accessible pilgrimage experience for Dhoyof Al-Rahaman

6. Recommendations

This section outlines key recommendations to improve wayfinding systems in Makkah's neighborhoods. Based on study findings, these suggestions aim to enhance navigation, safety, and overall experience for residents and pilgrims. The focus is on improving signage visibility, offering multilingual support, introducing distinct landmarks, upgrading pedestrian pathways, and involving the community. Regular assessments and emergency preparedness are also emphasized to ensure ongoing improvements and effective crowd management during Hajj and Umrah seasons. Here the key recommendations for this study:

- Improve the visibility and clarity of signage throughout Makkah's residential neighborhoods, ensuring that signs are well-lit, placed at strategic locations, and use clear language.
- Implement multilingual signage to accommodate the diverse linguistic backgrounds of pilgrims. This includes translations into major languages spoken by the visitors, such as English, Urdu, and Bangla.
- Introduce distinct urban identity markers and landmarks that can help orient visitors. This could include culturally significant architectural features.
- Upgrade and maintain pedestrian pathways and sidewalks to ensure they are safe and accessible, especially during peak seasons. This helps facilitate smooth movement through crowded areas.
- Increase the availability of well-trained local guides who can assist pilgrims in navigating the neighborhoods, providing information on routes and nearby landmarks.
- Conduct regular assessments of the wayfinding systems to identify areas for improvement. This should include gathering feedback from residents and visitors to continuously enhance the navigation experience.
- Involve local residents in the design and implementation of wayfinding systems to ensure that they meet the needs of both the community and the pilgrims.
- Develop clear emergency response signage and protocols to ensure that pilgrims can quickly identify safe routes and access emergency services when needed.

By implementing these recommendations, Makkah can significantly improve the effectiveness of its wayfinding systems, enhancing the overall safety and experience for both residents and pilgrims during Hajj and Umrah seasons.

References

- Al-Ghamdi, K. A., Karban, A. S., Said, I., Rasidi, M. H., & Al-Ghamdi, S. A. (2021). Enrich Pilgrims Experience by Improving the Wayfinding System in (Meeqat Zul Halifa) Abiar Ali. The 20th Scientific Forum for the Hajj, Umrah, and Visit Research, 1, 427–436.
- Alinaghi, N., & Giannopoulos, I. (2024). Wayfinding Stages: The Role of Familiarity, Gaze Events, and Visual Attention. Leibniz International Proceedings in Informatics, LIPIcs, 315. https://doi.org/10.4230/LIPIcs.COSIT.2024.1
- Alkharoubi, A. M. (2020a). Wayfinding for Pedestrians in the Crowded Areas of Al-Hajj: How Can Wayfinding System Designs Increase the Efficiency of Wayfinding and Navigation Performances for Pedestrian Pilgrims During the Islamic Pilgrimage (Al-Hajj) [DOCTOR OF PHILOSOPHY]. UNIVERSITY OF MINNESOTA.
- Alkharoubi, A. M. (2020b). Wayfinding for Pedestrians in the Crowded Areas of Al-Hajj: How Can Wayfinding System Designs Increase the Efficiency of Wayfinding and Navigation Performances for Pedestrian Pilgrims During the Islamic Pilgrimage (Al-Hajj). https://conservancy.umn.edu/server/api/core/bitstreams/1f29e86e-a142-43f5-8201-470ea8d9f241/content
- Al-Rabiah, F. (2023). Scouts Guide 206,000 Lost Pilgrims during This Year's Hajj Season. Saudi Press Agency, 4–5. https://spa.gov.sa/en/68cc0bd997b
- Askarizad, R., Lamíquiz Daudén, P. J., & Garau, C. (2024). Exploring the role of configurational accessibility of alleyways on facilitating wayfinding transportation within the organic street network systems. Transport Policy, 157, 179–194. https://doi.org/https://doi.org/10.1016/j.tranpol.2024.09.001
- Baskaya, A., Wilson, C., & Özcan, Y. Z. (2004). Wayfinding in an unfamiliar environment: Different spatial settings of two polyclinics. Environment and Behavior, 36(6), 839–867. https://doi.org/10.1177/0013916504265445
- Bhatt, A., & Kolay, S. (2020). Spatial Heuristic Evaluation Through Wayfinding: A Tale of Two Indian Cities. In Advances in Intelligent Systems and Computing (Vol. 972, Issue August 2019, pp. 598–610). https://doi.org/10.1007/978-3-030-19135-1_59
- Boumenir, Y., Dresp, B., & Georges, F. (2010). Wayfinding through an Unfamiliar Environment. Perceptual and Motor Skills. https://doi.org/10.2466/04.22.23.27.PMS.111.6
- De Vera, M. A., Ratzlaff, C., Doerfling, P., & Kopec, J. (2010). Reliability and validity of an internet-based questionnaire measuring lifetime physical activity. American Journal of Epidemiology, 172(10), 1190–1198. https://doi.org/10.1093/aje/kwq273
- Farr, A. C., Kleinschmidt, T., Yarlagadda, P., & Mengersen, K. (2012). Wayfinding: A simple concept, a complex process. In Transport Reviews (Vol. 32, Issue 6, pp. 715–743). https://doi.org/10.1080/01441647.2012.712555
- Gazzawe, F., & Albahar, M. (2024). Reducing traffic congestion in makkah during Hajj through the use of AI technology. Heliyon, 10(1). https://doi.org/10.1016/j.heliyon.2023.e23304
- Hajj Statistics.(2023) .
- Iftikhar, H. (2022). A DESIGN FRAMEWORK FOR SYNTHESIZING THE MOBILE AND STATIC WAYFINDING INFORMATION IN COMPLEX ENVIRONMENTS [Thsis]. The Hong Kong Polytechnic University.
- Kadi, S., Abdullah, A., & Bachok, S. (2021). THE EVALUATION OF PEDESTRIAN FACILITIES ON HAJJ CROWD BETWEEN ARAFAT AND MUZDALIFAH PEDESTRIAN STREET. PLANNING MALAYSIA, 19. https://doi.org/10.21837/pm.v19i19.1069
- Karban, A. S. (2020). Reviving the Roles of Makkah Residents in Providing Hospitality. PalArch's Journal of Archaeology of Egypt/ Egyptoloy, 17(7), 13310–13332.
- Khalid, M. A., Rasidi, H., Suruje, A. F., Karban, A. S., & Alsolami, B. M. (2024). EasyChair Preprint Factors Influencing Wayfinding Systems Efficiency for Hajj Pilgrims in Al-Mashaaer Al-Mugaddassah Metro Train Station, Muzdalifah.
- Lynch, K. (1960). The Image of The City. 11.

- McCunn, L. J., & Gifford, R. (2018). Spatial navigation and place imageability in sense of place. Cities, 74, 208–218. https://doi.org/https://doi.org/10.1016/j.cities.2017.12.006
- Memon, M. A., Ting, H., Cheah, J. H., Thurasamy, R., Chuah, F., & Cham, T. H. (2020). Sample size for survey research: Review and recommendations. Journal of Applied Structural Equation Modeling, 4(2), i–xx. https://doi.org/10.47263/jasem.4(2)01
- Pallant, J. (2013). SPSS Survival Manual. McGraw-Hill Education.
- Passini, R. (1984). Wayfinding in Architecture. New York: Van Nostrand Reinhold.
- Phillips, J., Walford, N., Hockey, A., Foreman, N., & Lewis, M. (2013). Older people and outdoor environments: Pedestrian anxieties and barriers in the use of familiar and unfamiliar spaces. Geoforum, 47, 113–124. https://doi.org/10.1016/j.geoforum.2013.04.002
- Raineri, A. (2015). Behavioural risk at outdoor music festivals [University of Southern QueenslandVolume IApril 2015Supervisor: Prof Glen Postle]. https://doi.org/10.13140/RG.2.1.4615.1523
- Shiwakoti, N., Shrestha, R., & Aghabayk, K. (2023). State-of-the-Art Passengers Survey Examining Passengers' Crowd Behavior in Emergencies at Train Stations. In N. Bellomo & L. Gibelli (Eds.), Crowd Dynamics, Volume 4: Analytics and Human Factors in Crowd Modeling (pp. 179–200). Springer International Publishing. https://doi.org/10.1007/978-3-031-46359-4_7
- Tahir, R., & Krogstie, J. (2023). Impact of Navigation Aid and Spatial Ability Skills on Wayfinding Performance and Workload in Indoor-Outdoor Campus Navigation: Challenges and Design. Applied Sciences, 13(17), 9508. https://doi.org/10.3390/app13179508
- Umrah Statistics. (2023). https://doi.org/10.1080/01441647.2012.712555
- Wu, J., Chen, X., Zhao, M., & Xue, C. (2024). Cognitive characteristics in wayfinding tasks in commercial and residential districts during daytime and nighttime: A comprehensive neuroergonomic study. Advanced Engineering Informatics, 61, 102534. https://doi.org/https://doi.org/10.1016/j.aei.2024.102534
- Wu, K.-C., & Wang, H. (2017). Inclusive Design Thinking for Accessible Signage in Urban Parks in Taiwan. International Conference on Universal Access in Human-Computer Interaction, 335–347.
- Zhou, J., & Ujang, N. (2024a). An Analysis of Pedestrian Preferences for Wayfinding Signage in Urban Settings: Evidence from Nanning, China. Buildings, 14(9). https://doi.org/10.3390/buildings14092986
- Zhou, J., & Ujang, N. (2024b). An Analysis of Pedestrian Preferences for Wayfinding Signage in Urban Settings: Evidence from Nanning, China. Buildings, 14(9). https://doi.org/10.3390/buildings14092986

Patterns of Emergency Department Visits during Hajj Period in Al-Noor Specialist Hospital, Makkah, Saudi Arabia, 2024: Towards Healthcare Optimization in View of Saudi Arabia's Vision 2030

Ghanim. H. Al-Khattabi[1]*, Hatim. Ahmad. Al-Omari[1], Basmah. Amin. Rafea[1], Molham. Abdulfattah. Feda[1], Khulood Khaled Al-Harbi[2], Osaid. Ayman. Halwani[1]

Makkah Healthcare Cluster, Ministry of Health

*Corresponding author: E-mail (drghanimm@gmail.com)

أنماط زيارات قسم الطوارئ خلال فترة الحج بمستشفى النور التخصصي بمكة المكرمة، المملكة العربية السعودية 2024: نحو تحسين الرعاية الصحية في ضوء رؤية المملكة العربية السعودية 2030

غانم حميد الخطابي*[1]، حاتم أحمد العمري[1]، بسمة أمين رفيع[1]، ملهم عبد الفتاح فدا[1]، خلود خالد الحربي[2]، أسيد أيمن حلو اني[1]

تجمع مكة المكرمة الصحي، وزارة الصحة

Abstract:

Non-urgent hospital visits have become an increasing concern in Middle Eastern countries. However, there is remarkable paucity in studies that have elucidated the pattern of acute cases treated at the ultimate healthcare center during Hajj, including that described the urgency of emergency visits during this vital period. This study aimed to examine the pattern of emergency department visits (EDV) by patients during Hajj period and to determine the urgency of emergency visits at a specialist healthcare center. A retrospective review of medical records of Hajj patients visiting the ED at Al-Noor Specialist Hospital (NSH) in Makkah from 1-12-1445 H till 30-12-1445 H was conducted. A total of 14842 patient records included in the analysis, nearly two third 61.34% of them were male.

The most common provisional diagnoses were unspecified pain for further investigation 13.61%. Most of the patients who visited the ED were discharged 90.89% (avoidable visits). Only 4% of the ED visits led to hospital admission. Results from the Canadian Triage and Acuity Scale (CTAS score) revealed that more than two-thirds 69.82% of patients were triaged with a score of III; however, the scores changed significantly throughout the Hajj days and through different EDV duration ($p = 0.00$). Most of the EDVs 98.92% stay less than 1 hour in the ED and almost all of the EDV visitors do not follow up 98.96%. It was concluded that triaging patients during Hajj might be difficult due to the high number of patients relative to available resources. During Hajj, a significant proportion of patients who visited the ED at the ultimate healthcare facility were discharged within 24 hours, with a higher rate in the morning, afternoon and before mid-night period.

It was recommended that value-based health care and new model of care principals including urgent care pathway is currently warranted in addition to extension in working days at primary care centers and optimization of advanced

healthcare facilities during Hajj period, close collaboration between Emergency Department physicians and other physicians is required for efficient resource use. **Introduction**

Millions of Muslims visit Saudi Arabia's Holy City (Makkah or Mecca) each year for the Hajj pilgrimage. The rite takes place from 8 to 13 Dhul Hijjah, the last month of the Islamic year. Mass gatherings and overcrowding migration from one location to another, which distinguishes the Hajj season, raise the risk of infectious and noncommunicable medical diseases. Furthermore, emergency departments (EDs) receive a large number of cases involving acute diseases during Hajj, resulting in much higher rates of morbidity and mortality. Hajj, a journey to Makkah and holy locations, is one of the 5 pillars of Islam that every financially and physically capable Muslim must do once in their lives. It brings together Muslims of all colors and languages for one of life's most powerful spiritual experiences. Hajj, which brings together more than 2 million Muslims, provides a unique challenge for healthcare services. The primary objective of healthcare practitioners is to offer the best possible service to the greatest number of patients with the resources available. [1, 2] Various communicable and noncommunicable medical issues, including cardiovascular events, respiratory disorders, heat stroke, and trauma, have been documented among Hajj pilgrims visiting basic and secondary medical facilities. [3-5] Furthermore, heart disorders are widespread and urgently identified in advanced care facilities.[2, 6]. Nonurgent hospital visits have been a growing problem in Middle Eastern nations, with up to 88.7% of patients being classed as nonurgent at emergency departments. [7, 8] Two studies in Saudi Arabia investigated the scope of these possibly unnecessary visits during non-Hajj times, and discovered that 53% to 59.4% of patients visiting EDs had primary care or nonurgent diseases.[7, 9].

The Saudi Ministry of Health offers all Hajj pilgrims with free, high-quality health care services. As a result, during Hajj, Saudi authorities assigned 25,000 health staff and 25 hospitals, as well as 155 permanent and seasonal health facilities dedicated to delivering various levels of medical treatment. These services are offered at all four major ceremonial sites: Mina, Arafat, and the two Holy Mosques. Approximately 60% of patients hospitalized in these care centers are moved to advanced care institutions.[10] Al-Noor Specialist Hospital (NSH) is a tertiary care hospital in Makkah City that handles complicated problems and provides advanced treatment to all pilgrims visiting the location, including 24-hour emergency services.. Previous research on Hajj detailed the pattern of hospitalization among pilgrims, revealing various diagnoses in this population. [2, 6, 10, 11] However, no prior research has defined the pattern of acute cases treated at the final healthcare center during Hajj, nor has it highlighted the importance of emergency visits during this critical season. As a result, we sought to investigate the frequency of ED visits (EDVs) among Hajj patients and assess the urgency of EDVs during Hajj.

This would eventually contribute to maintaining a high level of readiness for Hajj-related possible calamities and optimizing big healthcare facilities throughout the pilgrimage. Previous studies on Hajj documented the pattern of admission among Hajj pilgrims, showing different diagnoses in this group. However, there is a notable lack of research that elucidates the pattern of acute cases treated at the final healthcare institutions during Hajj and describes the importance of emergency visits during this critical time.The current study's findings will be useful for future researchers, decision-makers, and study replication. Therefore, the objective of the current study was to identify the pattern of ED visits (EDVs) among all patients attending the ED during Hajj (including both pilgrims and non-pilgrims) in Al-Noor Specialist Hospital in Makkah from 1-12-1445 H till 30-12-1445 H, in addition the study aimed to determine the urgency of EDVs among all patients (including both pilgrims and non-pilgrims) in Al-Noor Specialist Hospital in Makkah from 1-12-1445 H till 30-12-1445 H

Methodology

The study was conducted at Makkah healthcare cluster hospitals after approval from its Institutional Review Board. (IRB Number: H-02-K-076-0624-1133). Retrospective data analyses were conducted using medical records of Hajj patients attending the ED during Hajj (including both pilgrims and non-pilgrims) in Al-Noor Specialist Hospital in Makkah from 1-12-1445 H till 30-12-1445 H by the researcher and his team. All patients attending the ED during Hajj (including both pilgrims and non-pilgrims) in Al-Noor Specialist Hospital in Makkah from 1-12-1445 H till 30-12-1445 H was included in the study, with no exclusion. During Hajj, patients who seek care at Makkah healthcare cluster facilities was triaged in emergency departments and either sent to the outpatient department for further medical care or treated there. They were discharged from the emergency department (these trips were thought to be possibly unnecessary), admitted to an inpatient institution after getting initial care, judged absconding, or reported deceased. Patients' medical records were analyzed to gather information on demographics, time of presentation in the ED, clinical diagnosis and comorbidities, disposition and time of disposition, language difficulties, and Canadian Triage and Acuity Scale (CTAS) score classification. [12]. All participants with missing data were excluded from the study using conventional statistical methods. The length of the ED Stay in (Hour) was measured for both admitted and released patients as the time between the EDV's start and hospital admission or discharge. CTAS assists healthcare personnel in determining the severity of situations during the triage stage. The grades range from I (need for resuscitation) to V (not urgent). EDV durations were divided into three equal periods: A (08:00 a.m.–03:59 p.m.), B (04:00 p.m.–11:59 p.m.), and C (12:00 a.m.–07:59 a.m.). The data were analyzed using SPSS version 21.0. Numerical data were given as means and standard deviations, or medians and interquartile ranges. ANOVA, T. Test, Mann-Whitney U tests, and Kruskal-Wallis tests were used to compare different data distributions. if P value equal or less than 5%, then the test result considered significant. The categorical variables were compared using chi-squared testing.

Results:

Tables from 1 to 16 show the results of the present study which concern with the patterns of emergency department visits during Hajj period in Al-Noor Specialist Hospital, Makkah, Saudi Arabia, 2024. Out of the 14842 patient records included in the analysis, 61.34% (n = 9104) were of men with a mean age of 25.5865 ± 2.19 years, and Saudis are the most common visitors 46.07% (n=6837) followed by Egyptian 8.55% (n=1269), Pakistani 4.83% (n=717), Hindi 4.55% (n=676), Indonesia 3.91%(n=580) and Yamani 3.71% (n=551) respectively. The results show that CTAS scores were III in more than two-thirds 69.82% of the EDVs, most of them were male 61.9% and 98.89% of them were with no previous medical condition and 93.39% of them were discharged and 91% of them attend the hospital walk in (**Table 3)**. The most common provisional diagnoses were unspecified pain for further investigation 13.61% (**Table 4)**. Most of the EDVs (90.89%) were discharged (avoidable visits), only 4% of the ED visits led to hospital admission and the highest proportion of discharged visits occurred during Period A (35.58%) and 61.8% of them were male (**Table 5).** The length of stay for ED visitors for less than 1 hour for discharged cases was 90.89%, compared with those for admitted cases 4.1% **Table 6** while the most common type of transportation for ED visitors was walk in 81.55% (around 61.5% of them were male **(Table 7)**. Results in tables 8-16 show visiting times, durations, and outcomes for 14842 EDVs show that most EDVs were encountered before midnight (Periods A and B; 69.81%) (period A 35.94% and period B 33.87%) compared to that after midnight in period C 30.19%. and male patients encountered around 60.3% from those EDVs in period A. Also, most of the EDVs 98.92% stay less than 1 hour in the ED and 61.5% of them were male and 36% of them are in period B, and

35.68% were in period A and 99% of them reported no previous medical condition and 98.8% of them stay less than one hour in ED) followed by ambulance 11.88% (around 60.7% of them were male and 40.24% were in period A and 98.4% of them reported no previous medical condition and 99.3% of them stay less than one hour in ED). Almost all of the EDVs visitors do not follow up 98.96%. Approximately, 99% of them reported no previous medical condition and 99% of them stay less than 1 hour in ED, and 86.5% of them attend to the hospital walk in. Admission occurred more frequently during Periods A and B (39.9% and 37.74%, respectively) than Period C (22.35%; $p < 0.000039$). There was a statistically significant difference observed ($p = 0.00$ %) between EDV duration and CTAS score.

Table 1: Gender Data

Gender	Number	%
Female	5716	38.51%
Male	9104	61.34%
Unknown	22	0.15%
Total	14842	100%

Table 2: Nationality Data

Nationality	No	%	Nationality	No	%	Nationality	No	%
Saudi	6837	46.07%	Algerian.	129	0.87%	Bahraini	35	0.24%
Egyptian	1269	8.55%	Unknown.	128	0.86%	Malaysian.	32	0.22%
Pakistani	717	4.83%	Irani.	112	0.75%	Lebanese.	29	0.20%
Indian	676	4.55%	Tunisian.	106	0.71%	Libyan.	28	0.19%
Indonesian	580	3.91%	Jordanian.	91	0.61%	Siri Lanky.	25	0.17%
Yamani	551	3.71%	Chinese.	90	0.61%	Kuwaiti.	22	0.15%
Bangladesh.	390	2.63%	Philippine.	89	0.60%	British.	21	0.14%
Myanmar.	381	2.57%	Mali.	65	0.44%	Palestinian.	20	0.13%
Syrian.	295	1.99%	Unknown	50	0.34%	American.	19	0.13%
Iraqi.	278	1.87%	Uzbekistan.	49	0.33%	Francie.	17	0.11%
Afghani.	276	1.86%	Russian	48	0.32%	Mauritania.	16	0.11%
Sudani.	239	1.61%	Somali.	48	0.32%	Toggley.	15	0.10%
Moroccan.	232	1.56%	Tchadi.	47	0.32%	Omani.	14	0.09%
Turkey	181	1.22%	Niger.	43	0.29%	Girgestani.	14	0.09%
Nigerian.	160	1.08%	Ethiopia.	41	0.28%	Morisious	14	0.09%

Table 3: Severity Level According to Canadian Triage Acuity Scale (CTAS)

Canadian Triage Acuity Scale (CTAS)	Number	%
1	92	0.62%
2	1487	10.02%
3	10362	69.82%
4	356	2.40%
5	887	5.98%
Unknown	1658	11.17%
Total	14842	100%

Table 4: Provisional Diagnoses

Professional Diagnosis	Number	%
Accident	322	2.17%
Assault	13	0.09%
Cancer	17	0.11%
Cardiac	786	5.30%
Dental	9	0.06%

Dermatology	99	0.67%
Ent	36	0.24%
Fall	973	6.56%
Fever for Further Investigation	170	1.15%
Gastrology	968	6.52%
General Surgery	729	4.91%
Genital	14	0.09%
Heat Related Illness	236	1.59%
Metabolic-Related, Electrolyte Disturbance, Dehydration	1247	8.40%
Neurology	471	3.17%
Ophthalmology	114	0.77%
Orthopedic	196	1.32%
Other	3840	25.87%
Psychiatry	24	0.16%
Respiratory	1336	9.00%
Rheumatology	207	1.39%
RTA	248	1.67%
Trauma	423	2.85%
Unspecified Pain for Further Investigation	2020	13.61%
Urology	344	2.32%
Total	14842	100%

Table 5: Outcome

Outcome	Number	%
Admission to Regular Ward	604	4.07%
Discharge	13490	90.89%
Discharge against Medical Advice	341	2.30%
Emergency Department Mortality	407	2.74%
Total	14842	100%

Table 6: Length of Emergency Department (ED) Stay in (Hour)

Length Of Emergency Department (ED) Stay in (Hour)	Number	%
> 1	14681	98.92%
> 1 to 2	97	0.65%
> 2 to 3	14	0.09%
> 3 to 4	10	0.07%
> 5	17	0.11%
Unknown	23	0.15%
Total	14842	100%

Table 7: Type of Transportation to Hospital

Type of Transportation to Hospital	Number	%
Ambulance	1763	11.88%
Mission offices	679	4.58%
Private Ambulance	132	0.89%
Walk-in	12103	81.55%
unknown	164	1.11%
Total	14842	100%

Table 8: Emergency Department Visits (EDVs) Periods and Outcome

Variables	Emergency department visits (EDVs) periods			Total	P. Value
Outcome	C (00:00 - 08:00)	B (16:00 - 00:00)	A (08:00 - 16:00)		
Admission to Regular Ward	135	228	241	604	0.000039%
Discharge	4144	4546	4800	13490	
Discharge against Medical Advice	82	110	149	341	
Emergency Department Mortality	120	143	144	407	
Total	4481	5027	5334	14842	

Table 9: Emergency Department Visits (EDVs) Periods and Canadian Triage and Acuity Scale (CTAS)

Variables	Emergency Department Visits (EDVs) Periods			Total	P. value
Canadian Triage and Acuity Scale (CTAS)	C (00:00 - 08:00)	B (16:00 - 00:00)	A (08:00 - 16:00)		
1	25	26	41	92	0.00%
2	399	532	556	1487	
3	3251	3540	3571	10362	
4	152	132	72	356	
5	238	212	437	887	
Unknown	416	585	657	1658	
Total	4481	5027	5334	14842	

Table 10: Gender and outcome

Variables	Gender			Total
Outcome	Unknown	Male	Female	
Admission to Regular Ward	1	329	274	604
Discharge	19	8347	5124	13490
Discharge against Medical Advice		199	142	341
Emergency Department Mortality	2	229	176	407
Total	22	9104	5716	14842

Table 11: Gender and Emergency Department Visits (EDVs) Periods

Variables	Gender			Total
Emergency Department Visits (EDVs) Periods	Unknown	Male	Female	
A (08:00 - 16:00)	9	3219	2106	5334
B (16:00 - 00:00)	8	3082	1937	5027
C (00:00 - 08:00)	5	2803	1673	4481
Total	22	9104	5716	14842

Table 12: Emergency Department Visits (EDVs) Periods and Type of Transportation to Hospital

Variables	Emergency Department Visits (EDVs) periods			Total
Type of Transportation to Hospital	C (00:00 - 08:00)	B (16:00 - 00:00)	A (08:00 - 16:00)	
Ambulance	472	582	710	1764
Mission Offices	234	275	170	679
Private Ambulance	13	45	74	132
Walk-in	3724	4060	4319	12103
Unknown	38	65	61	164
Total	4481	5027	5334	14842

Table 13: Length of Emergency Department (ED) Stay (Hour) and Emergency Department Visits Period

Variables	Length of emergency department (ED) Stay (Hour)						Total
Emergency Department Visits Period	Unknown	> 5	> 3 to 4	> 2 to 3	> 1 to 2	> 1	
A (08:00 - 16:00)	11	6	3	1	23	5290	5334
B (16:00 - 00:00)	8	7	3	2	45	4962	5027
C (00:00 - 08:00)	4	4	4	11	29	4429	4481
Total	23	17	10	14	97	14681	14842

Table 14: Canadian Triage and Acuity Scale (CTAS) and Outcome

Variables	Outcome				Total
Canadian Triage and Acuity Scale (CTAS)	Emergency Department Mortality	Discharge against Medical Advice	Discharge	Admission to Regular Ward	
1		30	51	11	92
2	57	11	1163	256	1487
3	350	2	9678	332	10362
4			351	5	356
5			887		887
Unknown		298	1360		1658
Total	407	341	13490	604	14842

Table 15: Type of Transportation to Hospital and Canadian Triage and Acuity Scale (CTAS)

Variables	Type of Transportation to Hospital					Total
Canadian Triage and Acuity Scale (CTAS)	Unknown	Walk-in	Private Ambulance	Mission offices	Ambulance	
1		23	3	1	65	92
2		734	18	67	668	1487
3	2	9445	21	250	644	10362
4		328		24	4	356
5		865		9	13	887
Unknown	162	708	90	330	370	1658
Total	164	12103	132	679	1764	14842

Table 16: Outcome and Length of ED Stay (Hour)

Variables	Outcome					Total
Length of ED Stay (Hour)	Emergency Department Mortality	Discharge Against Medical Advice	Discharge	Admission to Regular Ward	Length of ED Stay (Hour)	
> 1	399	341	13339	602	> 1	14681
> 1 to 2	6		91		> 1 to 2	97
> 2 to 3			13	1	> 2 to 3	14
> 3 to 4			10		> 3 to 4	10
> 5	2		14	1	> 5	17
Unknown			23		Unknown	23
Total	407	341	13490	604	Total	14842

Discussion

This study looked at the frequency of EDVs for Hajj patients as well as the urgency of their visits. Male and middle age visitors & Hajjis were predominant in the current study, since the distribution of sex was similar to that documented in other studies exploring Hajj (61.34% (n = 9104) were of male), Compared to the younger mean age of patients (25.5865

± 2.19 years) than other similar studies. [2, 3]This may imply a shift in the habitual behavior of most pilgrims (as recorded in previous comparable researches) who had saved their money for decades to conduct this Islamic rite, particularly the elderly. Changing the typical habits of evaluating illness patterns during the Hajj for just elderly people in many previous hajj research should be taken into account. Apart from regular pattern of EDV by Saudi people 46.07% (n=6837), Egyptian 8.55% (n=1269), Pakistani 4.83% (n=717), Hindi 4.55% (n=676), Indonesia 3.91%(n=580) and Yamani 3.71% (n=551) are encountered from the most EDV which need further care. More investigation to explore reasons for these high number compared to other nationalities are recommended. Most patients in our study were seen at the ED during the day, evening and before mid-night (Periods A and B), (Periods A and B; 69.81%) (period A 35.94% and period B 33.87%) compared to that after midnight (period C 30.19%) which coincided with most Hajj activities. This might be due to the fact that major emergency diseases typically arise during crowded mass movements. During Mina rites, multiple pilgrim groups go toward Jamarat at the same time, just before sundown, which corresponds to the start of Period B. In reality, the tragic Hajj stampede in Mina in 2015, which corresponded with the research, happened at this period (Period B). Furthermore, this period follows a period with an unsuitable pattern of EDVs (Period A), in which the greatest proportion of possibly avoidable visits occurred. As a result, full occupancy of emergency beds and suboptimal utilization of healthcare facilities and resources may be observed at the start of this important time (periods B). Despite variations in visit patterns, there was a significant difference in CTAS scores across periods. There was a statistically significant difference ($p = 0.00\%$) between EDV length and CTAS score, as well as when compared across patients' outcomes ($p < 0.0000\%$). 34.46% of cases with CTAS score III attend the emergency department in period A, 34.1% in period B, and 31.3% in period C. More over two-thirds of participants had CTAS scores of III 69.82% of the EDVs, the majority of them were male 61.9%, and 98.89% of them had no previous medical condition. Near to 93.39% of them had been discharged, and 91% attended the hospital walk-in.

This means that more than two-thirds, or 69.82%, of the EDVs had conditions that might possibly evolve to a major issue needing immediate intervention. May cause substantial discomfort or impair ability to operate at work or in everyday activities. Vital signs are typically normal, or near the top and lower limits of the normal range. These patients have an obvious risk for deterioration, yet are frequently allocated to the ED waiting room due to our overcrowding concerns, therefore we need to concentrate on these patients and offer efficient, effective, comprehensive treatment and resources.

During Hajj, 90.89% of patients who visited the emergency department has been discharged (avoidable visits). Most of these possibly preventable visits occurred in the morning, afternoon, and before midnight. Almost one-third (35.58%) of them happened during Period A, and around two-thirds (61.8%) were male. 99% of them had no prior medical history, and 84.5% went to the hospital walk-in. Because primary health care centers are regarded as one of the most appropriate facilities for such cases and avoidable ED visits, an extension of working days at primary healthcare centers, as well as the optimization of large facilities, are currently required to provide optimal care for visitors and pilgrims during Hajj. Approximately 90.89% of patients seen in the emergency department have been discharged without being hospitalized for additional treatment or sent to another hospital. It is worth noting that the Saudi government offers high-quality care and convenient access to hospitals to all Hajj pilgrims, even those with less serious diseases. The extent to which patients with non-serious diseases were presented to the ED, as well as their impact to the delay in patient flow, is still debated. Some studies done in the United States and Canada found impacts of these variables on waiting times, [13-15]whereas others found only minor effects on waiting times for other ED patients [16]. Inappropriate utilization of emergency department facilities occurs for a variety of reasons, although patient desire appears to be the most prevalent issue [14].

It is commonly acknowledged that unnecessary EDVs raise healthcare expenses and result in inefficient healthcare delivery. [17]This is important to note since Saudi Arabia has just released a promising national vision ("KSA Vison 2030") that aims to develop a successful economy and meaningful lifestyles for residents while encouraging physical well-being. [18] However, several studies done in the United States found relatively minimal savings when non-severe patients could be directed elsewhere. [19, 20] Nevertheless, Nonetheless, competent healthcare delivery leads to more efficient healthcare service consumption and better patient outcomes. Healthcare in EDs is more expensive than in other primary care settings ; [17] hence, efficient resource use is required. Shortening the waiting time for cases that require urgent care and admission is recommended, because there was a statistically significant difference between the length of EDV stay durations in the ED between potentially avoidable cases 90.89% (discharged) and those admitted and requiring further treatment (P. value 0.000039%), because the length of stay for ED visitors for less than 1 hour for discharged cases was 90.89%, compared with those for admitted cases 4.1%. Furthermore, the current study found that the length of ED stay (in hours) varied for both groups of patients (those admitted and discharged). This disparity may benefit the former. Because case admissions occur more frequently during Periods A and B (39.9% and 37.74%, respectively) than Period C, additional allocation for resources in those periods is necessary. The majority of EDVs (98.92%) spent less than an hour in the ED; 61.5% were male, and 36% were in period B. The average duration of EDVs was less than an hour, which is below the worldwide threshold. [21, 22] However, research in UK emergency departments found that visit lengths varied depending on the admission hour and patient characteristics.[22]. Previous research on illness trends during the Hajj found a high prevalence of noncommunicable diseases and chronic disorders among the elderly. The majority of published Hajj studies found that respiratory, cardiac, neurological, and gastrointestinal illnesses were frequent among pilgrims admitted to hospitals for medical care during the Hajj. [2, 3, 10, 11, 23] Furthermore, most studies found that respiratory disorders were the primary reason of hospitalization during Hajj, [3, 10, 11, 23] although in the current study, it was the second most prevalent cause of EDVs (9.00%). The leading cause of EDVs in the current research was nonspecific discomfort that required additional examination, accounting for around 13.61% of all patients. Khan et al. [2] found a significant prevalence of cardiovascular disease (34%).Furthermore, in Al-Mashaer facilities, prevalent comorbidities recorded for hospitalized patients during Hajj were asthma and chronic obstructive lung disease (22.5%), hypertension (17.5%), and diabetes mellitus (15%) [10]. The most common provisional diagnoses were unspecified pain for further investigation 13.61%, respiratory diseases (9.00%), metabolic-related & electrolyte disturbance & dehydration (8.40%), fall 6.56%, gastrologic 6.52%, and cardiac 5.30%. More arrangements for transportation of patients are recommended since the most common type of transportation for ED visitors was walk in 81.55% (around 61.5% of them were male and 35.68% were in period A and 99% of them reported no previous medical condition and 98.8% of them stay less than one hour in ED) followed by ambulance 11.88% (around 60.7% of them were male and 40.24% were in period A and 98.4% of them reported no previous medical condition and 99.3% of them stay less than one hour in ED). More plans for patient follow-up are suggested, since practically all EDVs visitors fail to follow up (98.96%). Notably, most studies reported mortality rates ranging from 0.6% to 16% [2, 11], but the current study observed just 2.74% of fatalities. The current study found that the average mortality rate for EDVs was 2.74%, which was lower than the range of most published worldwide studies (0.6%–16%). [11] This could be partially attributed to the highly developed and adequately equipped ED at Al-Noor specialist hospital; however, we did not consider mortality data after admission to in-patient care units. Appropriate screening of prospective pilgrims for cardiovascular risk factors and adjustment to their treatment during the Hajj has decreased morbidity and mortality

in them.[24] . However, different screening methods could influence morbidity and mortality. Additionally, we have reported just 3 cases of meningitis. This is mostly due to the stringent control of vaccinations administered to pilgrims planning to visit Makkah during the Hajj. From the patients' perspective, it is uncertain if preventable ED cases would receive better care elsewhere. However, primary or secondary care institutions are regarded as the most equipped for such cases. One limitation of the study was the lack of a comparison to patients at any hospital in Al-Mashaer during the same time period. Potential disparities in health-seeking behavior between Al-Noor Specialist Hospital and any hospital in Al-Mashaer might help determine whether unnecessary visits are a Hajj-specific or broader issue. As a result, further research is needed to uncover appropriate strategies for advanced healthcare facilities to focus on severe and urgent situations while still providing cost-efficient services

Conclusion & recommendations

Triaging patients during Hajj might be difficult due to the high number of patients relative to available resources. Close collaboration between Emergency Department physicians and other physicians is required for efficient resource use. Admissions should be prioritized depending on patients' potential benefits. During Hajj, a significant proportion of patients who visited the ED at the ultimate healthcare facility were discharged within 24 hours, with a higher rate in the morning, afternoon, and before midnight period. Both admitted and discharged (avoidable) cases received equal levels of care leading to inappropriate use of ED facilities, contributing to higher healthcare costs, and leading to poor cost efficiency in healthcare delivery. Therefore, value-based health care and a new model of care principles including urgent care pathways are currently warranted in addition to extension in working days at primary care centers and optimization of advanced healthcare facilities during the Hajj period.

References:

1. Salmon-Rousseau, A., et al., Hajj-associated infections. Medecine et maladies infectieuses, 2016. **46**(7): p. 346-354.
2. Khan, N.A., et al., Pattern of medical diseases and determinants of prognosis of hospitalization during 2005 Muslim pilgrimage Hajj in a tertiary care hospital. A prospective cohort study. Saudi medical journal, 2006. **27**(9): p. 1373-1380.
3. Yousuf, M., et al., Pattern of medical problems among Haj pilgrims admitted to King Abdul Aziz hospital, Madinah Al-Munawarah. Annals of Saudi medicine, 1995. **15**(6): p. 619-621.
4. Alzeer, A., et al., Tuberculosis is the commonest cause of pneumonia requiring hospitalization during Hajj (pilgrimage to Makkah). Journal of infection, 1998. **36**(3): p. 303-306.
5. Balkhy, H.H., et al., Influenza a common viral infection among Hajj pilgrims: time for routine surveillance and vaccination. Journal of travel medicine, 2004. **11**(2): p. 82-86.
6. Mirza, A.A., et al., Patterns of Inpatient Admissions during Hajj: Clinical conditions, length of stay and patient outcomes at an advanced care centre in Makkah, Saudi Arabia. Pakistan journal of medical sciences, 2018. **34**(4): p. 781.
7. Dawoud, S.O., et al., Utilization of the emergency department and predicting factors associated with its use at the Saudi Ministry of Health General Hospitals. Global journal of health science, 2016. **8**(1): p. 90.
8. Shakhatreh, H., et al., Use and misuse of accident and emergency services at Queen Alia Military Hospital. JR Med Serv, 2003. **10**(1): p. 44-47.
9. Siddiqui, S. and D.O. Ogbeide, Utilization of emergency services in a community hospital. Saudi medical journal, 2002. **23**(1): p. 69-72.
10. Al-Rashed, R.S., Pattern of admission to hospitals during muslim pilgrimage (Hajj). Saudi Med J, 2003. **24**(10): p. 1073-1076.
11. Alzahrani, A.G., et al., Pattern of diseases among visitors to Mina health centers during the Hajj season, 1429 H (2008 G). Journal of infection and public health, 2012. **5**(1): p. 22-34.

12. Bullard, M.J., et al., Revisions to the Canadian emergency department triage and acuity scale (CTAS) guidelines 2016. Canadian Journal of Emergency Medicine, 2017. **19**(S2): p. S18-S27.

13. Burnett, M.G. and S.A. Grover, Use of the emergency department for nonurgent care during regular business hours. CMAJ: Canadian Medical Association Journal, 1996. **154**(9): p. 1345.

14. Sempere-Selva, T., et al., Inappropriate use of an accident and emergency department: magnitude, associated factors, and reasons—an approach with explicit criteria. Annals of emergency medicine, 2001. **37**(6): p. 568-579.

15. Richardson, L.D. and U. Hwang, Access to care a review of the emergency medicine literature. Academic Emergency Medicine, 2001. **8**(11): p. 1030-1036.

16. Schull, M.J., A. Kiss, and J.-P. Szalai, The effect of low-complexity patients on emergency department waiting times. Annals of emergency medicine, 2007. **49**(3): p. 257-264. e1.

17. Baker, L.C. and L.S. Baker, Excess cost of emergency department visits for nonurgent care. Health affairs, 1994. **13**(5): p. 162-171.

18. His Royal Highness Prince Mohammed bin Salman bin Abdulaziz Crown Prince, Vice President of the Council of Ministers Chairman of the Council of Economic and Development Affairs, Kingdom of Saudi Arabia. Saudi Vision 2030 (March 2019) https://vision2030.gov.sa/en/foreword.

19. Williams, R.M., The costs of visits to emergency departments. New England Journal of Medicine, 1996. **334**(10): p. 642-646.

20. Williams, R.M., The costs of visits to emergency departments—revisited. Annals of emergency medicine, 2005. **46**(5): p. 471-472.

21. Herring, A., et al., Increasing length of stay among adult visits to US emergency departments, 2001–2005. Academic Emergency Medicine, 2009. **16**(7): p. 609-616.

22. Karaca, Z., H.S. Wong, and R.L. Mutter, Duration of patients' visits to the hospital emergency department. BMC emergency medicine, 2012. **12**: p. 1-14.

23. Madani, T.A., et al., Causes of hospitalization of pilgrims during the Hajj period of the Islamic year 1423 (2003). Annals of Saudi medicine, 2006. **26**(5): p. 346-351.

24. Afshin-Nia, F., et al., How to reduce cardiovascular mortality and morbidity among Hajj Pilgrims: A multiphasic screening, intervention and assessment. Annals of Saudi medicine, 1999. **19**(1): p. 55-57.

The Role of Artificial Intelligence and Molecular Research in Revolutionizing Virus Infection Studies and Global Health Measures

Ilham T Qattan

Taibah University

*Corresponding author: E-mail (iqattan@taibahu.edu.sa)

دور الذكاء الاصطناعي والأبحاث الجزيئية في إحداث ثورة في دراسات عدوى الفيروسات وتدابير الصحة العالمية

إلهام بنت طلعت بن محمود قطان

جامعة طيبة

Abstract

Infectious diseases, caused by pathogenic microorganisms, can be symptomatic or asymptomatic. Preventative measures include early detection, transmission prevention, and vaccine development. Artificial Intelligence (AI) is a powerful and promising tool for mankind, as it is the output of big data that needs to be cleaned, structured, and integrated. AI has been represented as an advanced technology to prevent or early detection of viral infections in health care systems. Despite significant advancements in molecular research and global health, there remains a gap in fully leveraging AI to enhance the study of virus infections and improve public health responses. The objective of the review was to examine the transformative role of AI in these areas by exploring its applications in drug discovery, genomic sequencing, protein structure prediction, epidemiological modeling, diagnostic tools, and personalized medicine. The review assessed AI's contributions to global health measures such as surveillance, public health decision-making, and vaccine development and distribution. By presenting relevant case studies, including the COVID-19 pandemic and influenza outbreaks, the review highlights how AI has revolutionized virus infection studies and global health strategies. Furthermore, it identified challenges and ethical considerations, including data privacy, security concerns, and bias in AI algorithms, and proposes future research directions and recommendations. This comprehensive analysis underscores the potential of AI to bridge existing gaps and foster advancements in virus research and public health, paving the way for more effective and timely responses to future outbreaks.

Keywords: COVID-19, Artificial intelligence, infection, Heath measures

Introduction

1.1. Background: Pathogenic microorganisms like bacteria, viruses, parasites, or fungi are the source of infectious diseases, which can have symptoms or not. Certain illnesses, such as HIV, might be mostly asymptomatic but, if left untreated, can have catastrophic effects (Agrebi & Larbi, 2020). Microbes of various kinds spread infectious diseases in different ways. For example, some viruses spread by direct physical contact, whereas others, like influenza, spread by droplets released after sneezing, coughing, or speaking to someone within a few meters of one other (Richard & Fouchier, 2016).

Infectious diseases were the primary cause of premature deaths and disability worldwide. During World War I, close quarters, poor personal cleanliness, and unusually large-scale transportation all contributed to the spread of the Spanish flu virus (Berche, 2022). Several competing countries intentionally withheld information about the number of people killed by influenza, which had fatal

consequences because the virus would spread in subsequent waves. Miscommunication and incorrect use of pandemic data could have caused a million-plus fatality cost (Hayami, 2015).

Pandemic infectious diseases like SARS, MERS, Ebola, and Zika viruses emerged in the twenty-first century (Meganck & Baric, 2021; Reperant & Osterhaus, 2017). Infection-related disorders like cirrhosis, liver cancer, stomach cancer, and worsening conditions like cardiovascular and respiratory ailments can all be prevented by controlling infections (Agrebi & Larbi, 2020). The best prevention is to detect early possible pandemics and stop transmission, blocking transmission and eventually reducing virus mutations, ultimately keeping the virus in a stage that vaccines can help fight.

1.2. Significance of AI in Molecular Research: Artificial Intelligence (AI) is a powerful and promising tool for mankind, as it is the output of big data that needs to be cleaned, structured, and integrated (Silver et al., 2017). AI is an outcome of using large amounts of data that must be cleansed, organized, and integrated. Big data is defined by its volume, velocity, variety, truthfulness, complexity, and variability. However, statisticians and bioinformaticians rather than data scientists are usually needed to support health-related research (Silver et al., 2017). In the context of omics generating hundreds of thousands of data points for gene polymorphism, gene expression, metabolomics, lipidomics, and proteomics, there is a need to develop better tools to identify specific cases from the overall orientation of the mass of data (Misra et al., 2019).

Early trend identification can be made possible by detecting weak signals before they gain prominence and significance. In medicine, this would entail determining a signature in a small number of people or a group of people and forecasting the clinical course of the remaining population (Agrebi & Larbi, 2020). AI systems constantly adjust their behaviour in response to changes and change their reactions. One of its most popular uses, machine learning (ML), aims to evaluate, comprehend, and resolve an issue (Injadat et al., 2021). Recent findings suggest that machine learning (ML) offers significance to image processing in situations where traditional methods are unable to detect early illness indications (Zhou et al., 2021).

The Internet of Things (IoT) is a growing network of devices and objects that collect information, such as smartphones and wearable's (Indrakumari et al., 2020). These devices generate continuous streams of data that can be used to better understand our lifestyle and improve vaccine designs. AI has been increasingly used in healthcare to enhance efficiency and effectiveness, supporting tasks such as administrative workflow, clinical documentation, patient outreach, image analysis, medical device automation, and patient monitoring (Lee & Yoon, 2021). Major applications of AI in healthcare include drug development and ambient assisted living (AAL). Deep learning algorithms, artificial neural networks with multiple processing layers, have been successfully adopted for computer-assisted drug discovery (Bohr & Memarzadeh, 2020).

1.3. AI in Viral Infection Diagnosis: In the fight against infectious diseases, authorities have implemented surveillance systems to detect individuals at risk. A thermal camera has been employed in Singapore airport terminals to check people's temperatures and identify those who have high temperatures (Sun et al., 2015). Mathematical modelling, which includes a system that classifies individuals at higher risk for influenza based on vital signs like heart rate, breathing rate, and facial temperature, has enhanced this process. Fuzzy clustering techniques have been applied to classify persons who pose a higher risk. These methods enhance membership value and act as a fuzzifier. ML methods, such as support vector machine (SVM) learning algorithm, Matlab, leave one out cross-validation (LOOCV) method, and nested one-versus-one (OVO) SVM, have been used to separate gene sequences from bacteria (Fraley et al., 2016). However, the accuracy of these tools has been affected in real-life biological samples, indicating the need for consideration of practicalities like sample quality and laboratory process duration. Artificial immune recognition systems (AIRS) have been developed to address this issue, using k-nearest neighbour (kNN) as a classifier. SVM, a more robust classifier, was applied to a tuberculosis cohort, achieving 100% accuracy, sensitivity, specificity, and Youden's Index (Agrebi & Larbi, 2020).

Malaria, a life-threatening and pandemic infection, has been the subject of intense research to develop cost-effective and novel diagnostic methods. ML algorithms have been developed to detect red blood cells infected with malaria using digital in-line holographic microscopy data (Go et al., 2018). The SVM-based AI methodology accurately separated healthy from infected RBCs for

training and testing sets. Epidemiological studies can be performed at the population level or at the patient's bed, and mathematical models can predict the size of emerging infectious diseases. Large datasets and prediction models exist for non-communicable diseases (NCD), and ML methods are used to estimate variables related to infection (Luo et al., 2015). Epidemiological studies can predict epidemics from small foyers, such as Kyasanur forest disease (Majumdar et al., 2018). Recent life-threatening outbreaks, such as Ebola, have pushed the community to innovate in prediction using ML, single-layer artificial neural network (ANN), logistic regression (LR), decision tree (DT), and SVM classifiers (Colubri et al., 2016).

1.4. Objectives: Despite significant advancements in molecular research and global health, there remains a gap in fully leveraging AI to enhance the study of virus infections and improve public health responses. Traditional drug discovery, genomic analysis, and epidemiological modelling methods are often time-consuming and less efficient in handling large-scale data and predicting complex biological interactions. This review aims to examine AI's transformative role in these areas by exploring its applications in drug discovery, genomic sequencing, protein structure prediction, epidemiological modelling, diagnostic tools, and personalized medicine. Additionally, the review aims to assess AI's contributions to global health measures such as surveillance, public health decision-making, and vaccine development and distribution, while presenting relevant case studies and identifying future research directions and challenges.

2. AI Applications in Virus Infection Studies

Various technological approaches have emerged to combat viral epidemics, including digital technologies like Internet of Things (IoT), wearable's, and AI (Chamola et al., 2020; Sim & Cho, 2022). With the installation of Near Field Communication (NFC), more mobile devices are able to interact with the IT system through the Internet of Medical Things (IoMT), which has combined biometric devices and software applications for healthcare services (Hassija et al., 2019; M., 2015; Rodrigues et al., 2018). Wearable devices (Hiremath et al., 2014), such as smart watches (Available:, 2020), Bluetooth location beacons (Berryhill et al., 2020), and telemedicine (Osmundsen et al., 2015; T., 2020), have been adopted due to their ability to monitor stress levels and physical fitness. AI has been recognized as a breakthrough since its inception in 1956 and can be an effective tool against viral epidemics (Huang, 2020). AI can be used for disease monitoring, risk prediction (M, 2020), risk prediction (Naudé, 2020), medical diagnosis (Schmitt, 2020), screening, treatment research (Ekins et al., 2015), virus modelling (Senior et al., 2020), and lockdown measures (Jiang et al., 2020).

AI technology recently made it possible to monitor the spread of COVID-19, identify patients at high risk, and manage infection in real time. By examining patient data, it is able to forecast the chance of death. AI can help combat the virus by providing population screening, healthcare support, alerts, and recommendations for infection controls (Bai et al., 2020; Haleem et al., 2020; Hu et al., 2020). As an evidence-based medical tool, it can improve patient planning, treatment, and reported outcomes, making it a valuable tool in the fight against COVID-19 (Vaishya et al., 2020).

However, existing IoT and AI technologies have a limited impact on infection control due to their limited application to outbreaks. In situations where epidemics spread rapidly across countries, regional restrictions do not prevent large-scale infections and global spread through rapid prediction, resulting in large-scale loss of lives (Sim & Cho, 2023). Below are a few of the AI applications in viral infections.

2.2. Data Mining and Analysis: Emergent viral diseases pose a global challenge for public healthcare systems, with 1,399 human pathogen species, including 87 first reported in humans after 1980, responsible for significant mortality, morbidity, and economic losses (Woolhouse & Gaunt, 2007). Viruses infect humans through direct infective strategies or through animals as reservoir hosts (Klongthong et al., 2020). The World Health Organization has documented multiple disease outbreaks in different regions over the past four decades due to viral agents like Ebola, Crimean–Congo haemorrhagic fever virus, Lassa virus, Rift Valley fever virus, Marburg virus, Middle East respiratory syndrome-related coronavirus, Nipah virus, and severe acute respiratory syndrome coronaviruses (Organization, 2015).

The growth of Big Data has accelerated data analytics and knowledge discovery, with researchers focusing on producing usable knowledge in various domains. AI methods have been encouraged for effective infectious disease management and prevention, aiming to mitigate disease spread and contain outbreaks. Data analysis steps include data extraction, cleaning, pre-processing, transformation, interpretation, and evaluation (Nousi et al., 2022). The studies based on the utilization different methods of AI for the detection of significant viruses have been represented in Table 1.

Table 7 AI Based Detection Methods

S .No	Author(s)	Virus	Technology Used	Result
1	(Klongthong et al., 2020)	Chitosan-related viral disease treatment	Bibliometric predictive intelligence model, cross correlation, factor mapping, emergent scores	Identified three major research groups: drug delivery and adjuvants, vaccines and immune response, and tissue engineering. Highlighted that chitosan-based treatments for viral diseases are mostly in the in vitro stage of development.
2	(Frias et al., 2021)	Hepatitis C virus (HCV)	Data mining, predictive modeling, partial decision trees, ensemble models	Improved classification accuracy of HCV outcomes by identifying genetic patterns missed by conventional statistics. Partial decision trees and ensemble models increased accuracy compared to conventional methods.
3	(Saleh & Rabie, 2023)	Monkeypox	Human Monkeypox Detection (HMD) strategy, Improved Binary Chimp Optimization (IBCO), Ensemble Diagnosis (ED) model	Developed a new AI-based detection strategy for early detection of monkeypox. Achieved high accuracy (98.48%), precision (91.1%), and recall (88.91%) through feature selection and diagnostic algorithms.
4	(Ge et al., 2024)	HIV/AIDS	Data mining, IBM's Intelligent Miner, clustering, association rule discovery	Identified patient groups with common characteristics, errors in data, and unexpected associations in HIV/AIDS patient data. Facilitated better resource management and disease targeting.
5		Norovirus	Wavelet transform AI algorithm, data mining, epidemiological analysis	Improved clarity of intestinal ultrasound images and achieved a high positive detection rate (59%) for norovirus in children. Identified age groups and seasonal peaks of infection.
6	(Saad et al., 2018)	Hepatitis C virus (HCV)	Data mining, decision tree algorithm	Found a significant association between chronic HCV and diabetes mellitus (16.8%). Developed a decision tree model predicting fibrosis progression using attributes like AFP, age, and platelet count.
7	(Olsen et al., 2011)	Flaviviruses	Data mining, database integration, antigenic data analysis, T-cell epitope prediction	Assembled FLAVIdB database with antigen sequences, T-cell and B-cell epitopes, and molecular structures. Integrated data mining tools for vaccine target discovery.
8	(Liao & Tsai, 2007)	DNA viruses (HSV-1, EBV, CMV, HPV, HHV-8)	Data mining, clustering	Identified viral combinations related to breast cancer and fibroadenoma. Found protective effects of certain viral combinations on disease progression.
9	(Kebede et al., 2017)	HIV/AIDS	Cross-Industry Standard Process for Data Mining (CRISP-DM), WEKA, Random Forest, Neural Network, J48	Predicted CD4 count changes in ART patients with high accuracy using Random Forest algorithm. Identified baseline variables influencing CD4 count changes.
10		Swine flu (H1N1, H1N2, H3N1, H3N2, H2N3)	Naive Bayes classifier	Applied Naive Bayes classifier to detect swine flu, aiming to improve clinical decision-making and reduce examination costs.
11	(Andry et al., 2023; Tarasova et al., 2023)	COVID-19 (Omicron variant)	k-means algorithm	Divided data into 3 clusters of Omicron case distribution: low level (cluster 0), medium level (cluster 2), and high level (cluster 1).
12	(Tarasova et al., 2023)	HIV	Text-based identification of molecular mechanisms	Identified proteins and genes involved in HIV infection progression; verified impact in clinical studies.
13	(Kadhim, 2017)	Skin diseases	Decision tree and digital image processing	Improved classification accuracy of skin diseases using image data; system tested in MATLAB with various databases.

14	(Albahri et al., 2020)	COVID-19	A systematic review of automated AI applications for detection and diagnosis	Found gaps in AI research for COVID-19 detection; emphasized the need for more robust applications; analyzed reviewed studies' characteristics, challenges, and recommendations.
15	(Safdari et al., 2022)	HCV	Various classification models (SVM, Gaussian NB, DT, RF, LR, KNN) with SMOTE for data	The RF classifier showed the best performance, with 97.29% accuracy; the AUC for LR (0.921), KNN (0.963), DT (0.953), SVM (0.972), Gaussian NB (0.896), and RF (0.998) suggested potential for HCV stage identification.
16	(Gulyaeva et al., 2020)	Avian Influenza (AI)	ML, GIS, open access data sets	Modeled LP AI and its ecological niche with a 5 km pixel size; identified prevalence in Muscovy ducks, Mallards, Whistling Swans, and gulls; emphasized industrial impacts and wildlife contact zones.

2.2. Predictive Modeling for Viral Pathogenesis: Viral pathogenesis based on predictive modeling entails the utilization of computational approaches as well as statistical simulations in the given host organism to forecast the course of viral infections. By assessing parameters such as viral load, host immune response, the genetic variation within the population, and physical surroundings, the mechanistic models strive to predict consequences like the disease progression, communicability rates, and efficacy of interventional treatments (Restif & Graham, 2015). Such models may include simple regression equations where prognosis depends on certain factors to sophisticated mathematical models where prognosis takes into consideration various factors and interactions between the virus and the host. Based on a data collected from experimental works, clinical experiences, and epidemiological data, the predictive modeling makes great contributions to understanding the pathogenesis of the virus, to develop establishing strategies for public health, deciding clinical management, and to create new antiviral drugs and vaccines (Bhattacharyya, 2021). Several studies demonstrated the significance and efficacy of specific AI models for the prediction of Viral infection as discussed in Table 2.

Table 8: AI Models

S. No	Author	Virus	Objective	AI Model	Results
1	(Salehi et al., 2020)	SARS-CoV-2	To classify Coronavirus images and assess machine and deep learning-based architectures performance for automatic diagnostic tools	Convolutional Neural Network (CNN)	High accuracy in classifying X-Ray and CT images with potential clinical applications
2	(Kaushik et al., 2020)	SARS-CoV-2	To develop rapid, selective, sensitive diagnostic systems for early stage virus protein detection using AI for COVID-19 management	Nanoenabled miniaturized electrochemical biosensors supported by AI	Potential for rapid and selective detection at the picomolar level, interfacing with IoT and AI for data analytics
3	(Huang et al., 2020)	COVID-19	To understand and predict the spread of the virus	Susceptible-Infectious-Recovered (SIR) Model	Model accurately predicted the virus spread in different regions
4	(Cotugno et al., 2020)	Influenza Trivalent Inactivated Vaccination (TIV)	Developing a predictive score of immunogenicity	Deep ML algorithms using transcriptional data from sort-purified lymphocyte subsets after in vitro stimulation	Model accuracy of 95.6% with only one misclassified patient
5	(Khemasuwan et al., 2020)	SARS-CoV-2	To investigate the role of environmental factors in virus transmission	Epidemiological Modeling	Identified key environmental factors influencing virus spread
6	(Kara, 2021)	Influenza-like illness (ILI)	Improving multi-step influenza outbreak forecasting	LSTM neural network with genetic algorithm	Outperformance of other methods in peak period predictions
7	(Mottaqi et al., 2021)	COVID-19	Predict the number of confirmed cases	Convolutional Neural Network (CNN)	High prediction efficacy compared to other deep learning methods
8	(Gao et al., 2022)	COVID-19	Predict protein-protein interactions (PPIs) between SARS-CoV-2 and human proteins	Ensemble voting classifier using SVMRadial,	Greater accuracy, precision, specificity, recall, and F1 score

				SVMPolynomial, and Random Forest	
9	(Kavadi et al., 2020)	COVID-19	Predict global pandemic of COVID-19	Progressive Partial Derivative Linear Regression (PDR) and Nonlinear Machine Learning (NML)	Outperformed state-of-the-art methods in the Indian population
10	(Banerjee et al., 2020)	SARS-CoV-2	Predict SARS-CoV-2 positive patients from full blood counts	Random Forest, shallow learning, and a flexible ANN model	High accuracy in predicting SARS-CoV-2 positive patients
11	(Wang et al., 2021)	SARS-CoV-2	Predict COVID-19 diagnosis from CT images	Inception transfer-learning model	Proof-of-principle for using AI to extract radiological features for COVID-19 diagnosis
12	(Peng et al., 2021)	Hepatitis	Develop an explainable AI framework for hepatitis diagnosis	Logistic Regression, Decision Tree, K-Nearest Neighbor, eXtreme Gradient Boosting, Support Vector Machine, Random Forest	Improved transparency of complex models and insight into judgments
13	(Yang et al., 2020)	Various viruses	Predict human-virus protein-protein interactions (PPIs)	Unsupervised sequence embedding (doc2vec) + Random Forest classifier	Excellent predictive accuracy for known PPIs
14	(Ibrahim et al., 2021)	COVID-19	Classify CXR images for COVID-19, bacterial pneumonia, viral pneumonia, and normal scans	Deep learning approach using pretrained AlexNet model	High accuracy, sensitivity, and specificity for classification
15	(Malki et al., 2021)	COVID-19	Predict the period when the pandemic might end and the risk of a second rebound	SARIMA model	Predicted slowdown period and potential second rebound
16	(Sareen et al., 2017)	Zika Virus	Develop a system for preventing and controlling the spread of Zika virus disease -based risk assessment	Integration of fog computing, cloud computing, mobile phones, IoT-based sensor devices	High accuracy for initial diagnosis and GPS
17	(Fang et al., 2020)	Infectious Diarrhea	Develop a predictive model for incidence of infectious diarrhea	Random Forest model considering meteorological factors	Ideal prediction accuracy compared to classical ARIMA models
18	(Kaushik et al., 2020)	SARS-CoV-2	Determine the structure and potential functions of the Nsp2 protein	Cryo-electron microscopy combined with deep learning-based structure prediction	Identified zinc ion-binding site and potential roles in viral processes

2.3. Identification of Novel Therapeutic Targets: In recent years, AI has been widely utilized for the identification of novel therapeutic targets against significant viral infections to make the diagnostic process and treatments easier. In 2019, the outbreak of COVID-19 has effected millions of globally, However, the lack of significant identification and effective treatment methods remained a gap. As the drug discovery has been considered as an expensive and time consuming process typically takes around 10 years with high cost for the development of novel drugs in the market (Thomford et al., 2018). Target identification is defined as the process of identifying the specific biological sites, molecules or pathways that can be modulated or changed by the significant drugs for effective results. AI based algorithms has been recently emerged as an efficient and promising approach for the identification of specific therapeutics targets (Pun et al., 2023).

The rapid identification of several diseases lead to generate large of data, considered as a challenging situation for targeted therapy. Since AI has become effective at processing and managing complex biomedical networks of data, it may be used to identify patterns

and links in the data humans may overlook, which could improve our knowledge of and ability to treat diseases (Topol, 2019). AI has significantly improved the identification of biomarkers and targets, the prioritization of applications, the development of drug-like molecules, the prediction of pharmaceutical kinetics, the interaction between drugs and targets, and the design of clinical trials (Mak et al., 2023). Few of the AI based targeted interventions has been represented in Table 3.

Table 9: AI Based Targets

Virus	Target	AI Tools Used	Role of AI
SARS-CoV-2	Main protease (M^pro)	Deep learning, Molecular docking	Identification of essential viral protease as drug target
	RNA-dependent RNA polymerase (RdRp)	Machine learning, Molecular dynamics	Identification of essential viral polymerase as drug target
HIV	HIV-1 protease	Machine learning, Protein structure prediction	Identification of viral protease as antiretroviral target
	CCR5 co-receptor	Machine learning, Bioinformatics	Identification of cell co-receptor as entry inhibitor
Influenza	M2 ion channel	Deep learning, Structural bioinformatics	Identification of viral ion channel as drug target
	Hemagglutinin (HA)	Machine learning, Sequence analysis	Identification of conserved regions for vaccine development
Hepatitis C Virus (HCV)	NS5A protein	Deep learning, Protein-protein interaction prediction	Identification of viral protein as drug target
	Host cell factors	Machine learning, Network analysis	Identification of host factors for antiviral therapy

AI can navigate intricate biomedical networks and identify patterns and linkages in data that individuals might overlook (Mamoshina et al., 2018). Indication prioritization, drug-like molecule creation, pharmacokinetics prediction, drug-target interaction, and biomarker and target identification represent only a few areas where AI has significantly benefited clinical trial design. Clinical trials have revealed an increasing number of AI-derived medications, such as GS-0976 for non-alcoholic steatohepatitis, EXS-21546 for solid tumors, and INS018_055 for idiopathic pulmonary fibrosis (Pun et al., 2023). Several studies have demonstrated the AI based drugs along with their significant clinical trials. Few of these drugs has been represented in Table 4.

Table 10: AI-derived drugs in clinical trials

Company	Target	Indication	Compound	Development Status	Trial Number
BenevolentAI	Trk	Atopic dermatitis	BEN-2293	Phase 2	NCT04737304
Exscientia	A2AR	Solid tumors	EXS-21546	Phase 1	NCT04727138
	5-HT1A	Obsessive compulsive disorder	DSP-1181	Phase 1	Undisclosed
	5-HT1A/2A	Alzheimer's disease psychosis	DSP-0038	Phase 1	Undisclosed
	PKC-θ	Inflammatory diseases	EXS4318	Phase 1/2	Undisclosed
Insilico Medicine	Target X	Idiopathic pulmonary fibrosis	INS018_055	Phase 2	NCT05938920, CTR20230776
	3CLPro	COVID-19	ISM3312	Phase 1	CTR20230768
	USP1	BRCA-mutant cancer	ISM3091	Phase 1	NCT05932862
Nimbus Therapeutics	ACC	Nonalcoholic steatohepatitis	NDI-010976/GS-0976	Phase 2	NCT02856555, NCT03987074, NCT02891408, NCT02876796
Pharos iBio	FLT3	Acute myeloid leukemia	Radiation sensitizer	PHI-101	Phase 1
		Ovarian cancer			
		Triple-negative breast cancer			

Recursion Pharmaceuticals	CCM2	Cerebral cavernous malformation	REC-994	Phase 2	NCT05085561
	HDAC	Neurofibromatosis type 2	REC-2282	Phase 2/3	NCT05130866
	MEK1/2	Familial adenomatous polyposis	REC-4881	Phase 2	NCT05552755
Relay Therapeutics	SHP2	Solid tumors	RLY-1971/RG-6433	Phase 1	NCT04252339
	FGFR2	FGFR2-driven cancers	RLY-4008	Phase 1/2	NCT04526106
		Intrahepatic cholangiocarcinoma			
		Advanced solid tumors			
	PI3Kα	Solid tumors	RLY-2608	Phase 1	NCT05216432
Schrödinger	MALT1	Non-Hodgkin's lymphoma	SGR-1505	Phase 1	NCT05544019
Structure Therapeutics	GLP1R	Type 2 diabetes	GSBR-1290	Phase 1	NCT05762471
	APLNR	Pulmonary arterial hypertension	ANPA-0073	Phase 1	ACTRN12621000644864
		Idiopathic pulmonary fibrosis			
Valo Health	S1P1	Post-myocardial infarction	OPL-0301	Phase 2	NCT05327855
		Acute kidney injury			
	ROCK1/2	Diabetic retinopathy	OPL-0401	Phase 2	NCT05393284
		Diabetic complications			

ML-based algorithms, particularly deep learning methodologies, have gained significant attention in pharmaceutical areas (Carracedo-Reboredo et al., 2021). Multiple hidden layers of nodes are used in deep learning, commonly referred to as deep neural networks, for feature extraction and data processing. Current deep learning-based designs have been used in aging research, de novo small-molecule creation, pharmacological prediction of medications, and other areas of healthcare. Examples of these architectures are generative adversarial networks, recurrent neural networks, and transfer learning techniques (Aliper et al., 2016; Mouchlis et al., 2021).

Deep learning has been used in studies of fatal disorders with urgent clinical needs, such as identifying actionable therapeutic targets in amyotrophic lateral sclerosis (ALS) (Finkbeiner, 2024). Large language models, such as BioGPT and ChatPandaGPT, aid in therapeutic target discovery via rapid biomedical text mining. These models link genes, diseases, and biological processes, making it possible to quickly identify molecular mechanisms underlying the onset and progression of disease as well as possible targets for therapeutic intervention and biomarkers (Pun et al., 2023). However, these models may not have the ability to determine the accuracy and appropriateness of the input data, perpetuating human biases and preconceived notions.

2.4. Vaccine Development and Optimization: The COVID-19 pandemic has led to a study using AI to design universal vaccines against SARS-CoV-2. The SARS-CoV-2 proteome was used across 100 HLA-A, HLA-B, and HLA-DR alleles in the human population and generated comprehensive epitope maps. Monte Carlo simulations were used to identify "epitope hotspot" regions in the virus that are most likely to be immunogenic across a broad spectrum of HLA types (Malone et al., 2020). Across 3,400 distinct viral sequences, the immunogenic landscape and antigen presentation associated with each distinct mutation were also examined. A database containing the HLA haplotypes of over 22,000 people was used to create a digital twin simulation that represented various site combinations.

AI has been used to identify the genomic sequences of SARS-CoV-2 and variants of concern (VOC), develop drugs like Atazanavir, Remdesivir, Efavirenz, Ritonavir, Dolutegravir, PARP1 inhibitors, Abacavir, Roflumilast, Almitrine, and Mesylate, and develop vaccines using bioinformatics, databases, immune-informatics, ML, and reverse vaccinology (Bagabir et al., 2022). However, challenges include data collection difficulties, validation, ethical considerations, therapeutic effects, and clinical trial time. Table 4

includes examples of vaccines developed with the help of AI, along with the specific AI tools and their roles in the development process.

Table 11: AI Vaccines

S. No	Vaccine	Pathogen	AI Tool	Role of AI in Development
1	mRNA-1273 (Moderna)	SARS-CoV-2	Deep learning, sequence optimization	Identified spike protein target, optimized mRNA sequence
2	BNT162b2 (Pfizer-BioNTech)	SARS-CoV-2	Machine learning, immunogenicity prediction	Designed optimal mRNA sequence, predicted immune response
3	Flu vaccine candidates	Influenza	Predictive modeling, epidemiological analysis	Predicted circulating strains, selected vaccine strains
4	Epivax vaccine candidates	Various viruses	EpiMatrix (AI-driven epitope prediction)	Identified epitopes for peptide-based vaccines
5	CMV vaccine (VBI Vaccines)	Cytomegalovirus	Machine learning, sequence analysis	Identified conserved regions for broad immune response
6	Vaxign-ML vaccine candidates	Various pathogens	Machine learning, antigen prediction	Predicted protective antigens, accelerated vaccine design

3. Integration of AI with Epidemiological Aspects

Microorganisms such as bacteria, viruses and fungi, responsible for various type of infectious diseases that may lead to epidemic and sometimes pandemics in different nations or globally. These microorganisms have the capability to cause mild to severe infections with the symptoms like fever or diarrhoea (Agrebi & Larbi, 2020). despite the most recent developments in medical technology, infections continue to be the leading cause of death and morbidity worldwide, especially in low-income nations. Owing to recent developments in mathematical methods, scientists are now more capable to recognize the specificity of individual pathogens, anticipate outbreaks, and pinpoint possible targets for medication development (Jenner et al., 2020). AI and its components have been widely publicized for their ability to better diagnose certain types of cancer from imaging data (Hosny et al., 2018) .

AI has experienced rapid development and wide application in recent years, driven by big data and computing power. Techniques from traditional AI research areas like computer vision, speech recognition (Sarker, 2022), natural language processing (Bohr & Memarzadeh, 2020; Castro & New, 2016), and robotics (Habuza et al., 2021) have found innovative applications in various real-world settings, including medicine. Deep learning algorithms have also been applied to various fields, including public health surveillance. The growing literature on AI-enabled or enhanced public health surveillance, as shown in Figure 1, demonstrates the research community's interest in applying AI techniques. The COVID-19 pandemic has also prompted a call for AI-based public health solutions.

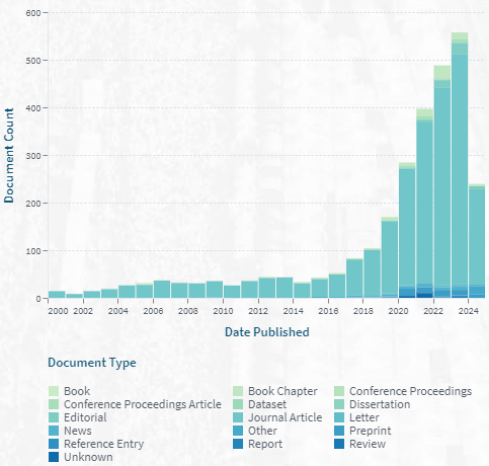


Figure 13: Literature on AI and Public Health Surveillance Over time

Numbers of published papers containing both "AI" and "public health surveillance" as keywords from the Lens, accessed in May 2024.

3.1 Real-time Surveillance Systems

Recent AI advances have significantly benefited public health surveillance, as evidenced by the growing literature on AI-enhanced surveillance work, highlighting the research community's interest in applying AI techniques. AI can enhance public health surveillance and response by addressing the fundamental challenges of data-driven surveillance. AI can address the issues associated with data sourcing and analytics by helping in the early, accurate, and reliable identification of health abnormalities and disease outbreaks from a variety of data sources. By simulating the dynamics of disease transmission, it can also be used to evaluate public health interventions and forecast and analyze changes in infectious disease trends. AI makes it possible to improve surveillance capabilities by utilizing new or unexplored data sources, such the Internet and Internet of Things apps. By addressing new forms of surveillance data, like text, photos, and videos that are semi-structured or unstructured, it also improves on the capabilities of existing data analytics tools. To provide early warning and forecast epidemic trends, machine learning techniques are able to recognize patterns, pinpoint anomalies, and evaluate trends and hazards from public health monitoring data streams. Few of the AI based Public Health Surveillance sites has been represented in Table 6.

Table 12: AI based Public Health Surveillance sites

Surveillance System	Description	AI Tools Used	Application in Viral Infection Identification
HealthMap	Aggregates data from news, social media, and public health sources to monitor disease outbreaks globally.	Natural language processing, machine learning	Identifies and maps reports of viral outbreaks globally, including emerging infections like COVID-19.
BlueDot	Tracks and predicts the spread of infectious diseases using data from multiple sources.	Machine learning, big data analytics	Predicts the spread of viral diseases, identifies hotspots for viruses like SARS-CoV-2.
ProMED-mail	Internet-based reporting system for emerging diseases and outbreaks.	Data filtering algorithms	Sorts and analyzes reports of viral outbreaks, aiding in early detection.
Flu Near You	Crowdsourced platform where users report flu-like symptoms to track influenza spread.	Machine learning	Tracks influenza trends and outbreaks, identifies viral flu patterns.
WHO's EIOS	Analyzes online information sources for early detection of health threats.	AI-driven data processing tools	Detects signals of emerging viral threats, facilitates early response to outbreaks.

3.2. Early Detection and Outbreak Prediction

Over the past two decades, numerous viral diseases such as Chikungunya, Ebola, Zika, Nipah, H7N9 Bird flu, H1N1, SARS and MERS have emerged, leading to increased risk of infectious disease outbreaks (Arora et al., 2020). The latest virus, COVID-19, has prompted the development of new surveillance strategies to detect emerging infections and identify increased risks associated with climate change. These strategies include event-based surveillance (EBS) systems and risk modelling (Bansal et al., 2020).

EBS systems use open-source internet data, such as media reports and social media, to detect emerging threats and enhance early warning of public health threats. AI applications, such as ML and natural language processing, are used to improve the speed, capacity, and accuracy of filtering, classifying, and analyzing health-related internet data. Risk modelling uses statistical and mathematical methods to assess disease severity and spread, considering factors like host, pathogen, and environment (Rees et al., 2019).

A study using maximum entropy ML (Walsh et al., 2017) has identified key determinants associated with Rift Valley Fever (RFV) emergence in Africa and the Arabic peninsula, including intermittent wetland, wild Bovidae richness, and sheep density as landscape suitability. A comparison study of the H5N1 outbreak in Egypt found that random forest was a more reliable prediction tool than ARIMA (Kane et al., 2014). An optimized ARIMA-GRNN model was utilized for forecasting and controlling tuberculosis in Heng county, China, despite high population movement and HIV coinfection history, demonstrating superior performance compared to previous models (Wei et al., 2017).

The utilisation of these strategies is expected to inform public health actions to prevent, detect, and mitigate the increase in infectious diseases due to climate change. The development of ML-based tools for healthcare providers offers novel ways to combat global pandemics, identifying trends and patterns in data. A few of the surveillance systems that have been utilised for the early detection of outbreaks have been represented in Table 7.

Table 13: Outbreak Surveillance systems

S. No	Studies	Surveillance System	Founded	Access	Moderation	AI Tools Used	Outbreak Detected	Impact of Early Detection
1	(Carrion & Madoff, 2017; Yu & Madoff, 2004)	Program for Monitoring Emerging Disease (ProMED)	1994 as a nonprofit organization	Yes	Partially moderated system	Data filtering algorithms	MERS-CoV (Middle East, 2012)	Identified initial reports, aiding in containment efforts.
2	(Dion et al., 2015)	Global Public Health Intelligence Network (GPHIN)	1998 through Canada-WHO partnership	No; available to partnered health agencies	Fully automated system	Machine learning, natural language processing	SARS (2002-2003)	Provided early warnings of the SARS outbreak.
3	(Alomar et al., 2015; Linge et al., 2010)	Medical Information System (MedISys)	2004 by the European Commission	Yes	Partially moderated system	Natural language processing, machine learning	H1N1 Influenza (2009)	Tracked spread and provided timely data to health officials.
4	(Harris et al., 2018; Hawkins et al., 2016)	HealthMap	2006 by Boston Children's Hospital	Yes	Partially moderated system	Natural language processing, machine learning	Ebola (West Africa, 2014), COVID-19 (2019)	Provided early warnings and real-time tracking.
5	(Valentin et al., 2020)	Pattern-based Understanding and Learning System (PULS)	Not specified	Yes	Not specified	Pattern recognition, machine learning	Various outbreaks	Improved early detection and response planning.
6	(Kasamatsu et al., 2021)	BlueDot	2013 by Kamran Khan	Yes	Fully automated system	Machine learning, natural language processing	COVID-19 (SARS-CoV-2)	Alerted clients before official announcements, enabling early preventive measures.
7	(Baltrusaitis et al., 2022)	Flu Near You	2011 by HealthMap and Boston Children's Hospital	Yes	Partially moderated system	Machine learning	Seasonal Influenza	Tracked real-time flu activity, allowing more effective responses.
8	(Jabour et al., 2021)	Google Flu Trends (Historical)	2008 by Google	No (Discontinued)	Fully automated system	Machine learning	Seasonal Influenza	Provided early indicators based on search queries.
9	(Yanagawa et al., 2022)	WHO's Epidemic Intelligence from Open Sources (EIOS)	2019 by WHO	No	Fully automated system	AI-driven data processing tools	Various viral outbreaks	Detected signals of emerging viral threats, enabling quicker response.

3.3. Contact Tracing and Transmission Dynamics Modeling

Recently, the COVID-19 pandemic presented significant uncertainty and variability, necessitating a comprehensive understanding of biological, policy, sociological, and infrastructure responses. Optimizing strategies for testing, diagnostics, contact tracing, and quarantine is crucial with asymptomatic spread and no immediate vaccine or pharmaceuticals. Interconnected system dynamics models were used to optimize mitigation strategies during a pandemic. A systems dynamics epidemiology model, along with other models, investigated uncertainties in testing and optimizes strategies for detecting and diagnosing infected people (Fair et al., 2021).

A study (Adeyemi et al., 2020) presented an epidemic model for COVID-19, focusing on intervention strategies such as social distancing, contact tracing, quarantine, case isolation, and supportive treatment. The model's feasibility and mathematical well-posedness were determined based on the threshold value, R0. Sensitivity analysis revealed that the rate of social distancing and rate of effective contact were the most sensitive parameters to the reproduction number.

Since the 1980s, modellers have been developing a consistent theory for contact tracing, aiming to find effective implementations and assess its effects on controlling emerging infectious diseases (Müller & Kretzschmar, 2021). Contact tracing is a crucial process for preventing infectious diseases, ensuring control and a long time to local take-off. It is vital during the SARS (Riley et al., 2003), Ebola (Saurabh & Prateek, 2017), and smallpox outbreaks (Eames & Keeling, 2003). With advancements in vaccine development technologies, contact tracing and follow-up control measures have become even more important. For novel pathogens like pandemic influenza, advanced technology may shorten the time needed for vaccine development, bridging gaps between epidemic emergence and vaccine availability (Kwok et al., 2019). Table 8 presented a few AI-based epidemic models focusing on contact tracing and transmission dynamics for different viruses

Table 14: AI-based epidemic models

Model Name	Virus	AI Tools Used	Purpose	Impact
COVID-19 Mobility Model	SARS-CoV-2	Machine learning, mobility data analytics	Predicting spread based on human mobility patterns	Informed travel restrictions and social distancing measures
DeepContact	Various (e.g., Influenza, SARS-CoV-2)	Deep learning, network analysis	Identifying and predicting high-risk contacts	Improved accuracy and efficiency in contact tracing
FluTracking	Seasonal Influenza	Machine learning, real-time data processing	Monitoring flu spread through self-reported symptoms	Enabled timely public health responses and resource allocation
ProNet (Proactive Network)	SARS-CoV-2	Machine learning, predictive analytics	Modeling transmission dynamics in real-time	Enhanced real-time response strategies and policy-making
EpiCAST (Epidemic Contact Analysis and Simulation Tool)	Various (e.g., Ebola, Zika)	Agent-based modeling, machine learning	Simulating transmission dynamics and contact tracing	Improved outbreak preparedness and response plans
OutbreakDetect	Various (e.g., Measles, MERS-CoV)	Machine learning, big data analytics	Early detection and prediction of outbreak spread	Facilitated rapid containment measures and resource deployment

2. Case Studies: AI-Molecular Research Integration in Virus Infections

2.1. COVID-19 Pandemic: Lessons Learned: The COVID-19 pandemic has led to an alarming increase in infections and deaths, with over 25,558,059 people infected and 860,311 dead by September 1, 2020 (Hopkins, 2020). Computational methods like molecular docking and molecular dynamics are being used to identify synthetic and natural drug candidates against SARS-CoV-2 (Pinzi & Rastelli, 2019). AI is also being used in drug and vaccine development to accelerate processes and reduce costs by facilitating rapid compound identification (Zhavoronkov et al., 2019).

AI tools, such as deep learning algorithms, were used in the development of mRNA vaccines by Pfizer-BioNTech and Moderna, accelerating the identification of optimal antigen targets and reducing the time required for vaccine development (Maharjan et al.,

2023). With the help of AI, potential therapeutic agents like remdesivir and dexamethasone against SARS-CoV-2, enabled rapid screening and identification of promising candidates for clinical trials (Rando et al., 2021).

AI tools like Nextstrain and GISAID have been used for genomic surveillance and variant tracking, enabling real-time monitoring of viral evolution and informing public health strategies (Ling-Hu et al., 2022). These tools have also been used for predictive modeling for public health interventions, such as forecasting COVID-19 case numbers and hospital resource needs (Kangabam et al., 2021). These models, enhanced by ML algorithms, provide governments and health organizations with accurate forecasts, enabling effective resource planning and allocation (Bullock et al., 2020).

During the COVID-19 pandemic, AI-driven tools played a pivotal role in public health interventions and diagnostics, significantly enhancing the global response to the crisis. Predictive modeling tools, such as SEIR (Susceptible, Exposed, Infectious, Recovered) frameworks (Guirao, 2020), ARIMA (AutoRegressive Integrated Moving Average) models (Singh et al., 2020), and advanced ML algorithms like random forests and gradient boosting machines (Chumachenko et al., 2022; Dash et al., 2022), were employed to forecast COVID-19 case numbers and hospital resource needs. These predictive models provided governments and health organizations with accurate and timely forecasts, enabling effective planning and allocation of medical resources, and optimizing interventions to mitigate the spread of the virus.

Additionally, AI-powered diagnostic tools, particularly convolutional neural networks (CNNs), recurrent neural networks (RNNs), and transformers such as PneuNet (Wang et al., 2023), CovidViT (Yang et al., 2023) and DenResCov-19 (Mamalakis et al., 2021) were used to develop diagnostic tests using CT and X-ray images (Dash et al., 2022). These AI-assisted diagnostics facilitated faster and more accurate detection of COVID-19, proving especially valuable in resource-limited settings where traditional methods might fall short. The deployment of these sophisticated AI tools not only accelerated the detection and management of COVID-19 but also set new standards for handling future pandemics with greater efficiency and precision.

2.2. Influenza Outbreaks: Improving Preparedness Strategies: The use of AI in responding to cases of influenza has enhanced preparedness for these perennial diseases by increasing surveillance, screening, and response capacity. AI tools like HealthMap and Flu Near You were used for early detection and surveillance of influenza outbreaks. HealthMap aggregated news reports and social media data to detect early signs (Ganser et al., 2022), while Flu Near You tracked flu activity in real time (Shapiro et al., 2021). These tools enabled health authorities to respond swiftly to emerging outbreaks. Google Flu Trends, a historical example, used ML models to predict flu activity and demonstrated the potential of AI for real-time prediction, which can inform vaccination campaigns and resource allocation (Radin et al., 2020).

Nextstrain uses AI tools like phylogenetic analysis and ML to analyze genomic data from influenza viruses, tracking their evolution and spread (Ekpenyong et al., 2021). This real-time surveillance helps identify emerging strains and informs vaccine formulation. AI-driven logistics platforms use ML and optimization algorithms to optimize vaccine production and distribution, predicting demand and identifying efficient routes (Qayyum et al., 2024). This reduces wastage and improves coverage, making vaccines more accessible and effective against prevalent strains.

Additionally, AI-powered chatbots and virtual health assistants are being used in public health campaigns to provide accurate and timely information about influenza prevention and treatment, enhancing the effectiveness of these campaigns by effectively addressing individual queries (Favour & Potter, 2024).

3. Challenges and Ethical Considerations

The application of the AI in virus infection research and broad public health initiatives offers certain possibilities and controversies that must be resolved to facilitate its effective utilization.

3.1. Concerning Data Privacy and Security: Data privacy and security are crucial in applied AI applications in health because these applications may rely on vast datasets containing personal identifiers and other confidential information (Thapa & Camtepe, 2021). Health data that is collected from individuals under ML algorithms is also exposed to cases of hacking compared to other personal

data. For instance, contact tracing apps compile data on individuals' whereabouts and health conditions; concerns arise about data storage, protection, and dissemination (Siddiq, 2023). To minimize these privacy threats, proper encryption techniques should be put in place, sensitive data should be anonymized as far as possible, and data protection laws, including GDPR in Europe and HIPAA in the United States, must be followed (Minssen et al., 2020; Tzanou, 2023).

However, data security has been another challenge that is also of equal importance as the issue of privacy (Tewari & Gupta, 2020). Electronic health records, general hospital databases, big data, and AAAI all provide ideal opportunities for cybercriminals to disrupt essential data (Mateus-Coelho & Cruz-Cunha, 2023). They can negatively affect healthcare facilities' functioning and disclose patient information. Thus, increasing investment in cybersecurity is vital to protect against these threats. This includes using higher levels of security measures, using security checks often, and having effective contingency measures to counter any security incidents in the fastest way possible (Mateus-Coelho & Cruz-Cunha, 2023).

3.2. Potential for Bias in AI and Automated Decision-Making: Another critical concerns in the use of AI in Health studies and interventions is the preconception that decisions made by AI have inherent bias (Dlugatch et al., 2023). Some of the potential causes of bias includes the data set that was used for the creation of the models and the structure of the algorithms that were used for development of the models (Fazelpour & Danks, 2021). There is a possibility that much of the training data is far from the rest of the population, which means that the AI models developed will only be able to deliver biased results that affect specific groups. For example, an AI model, which learned mostly from data of a specific group of patients, may need to generalise better to other populations in the delivery of healthcare services (Fletcher et al., 2021).

Additionally, if not controlled, the AI algorithms could end up replicating the existing bias when it is being developed. This can lead to unfair decision making that perpetuates inequality in the health sector and the quality of services rendered (Guidance, 2021). The question of diversity in training datasets is crucial, and they should include various population subsets to consider as many health conditions and reactions as possible (Nazer et al., 2023). Moreover, the transparency in AI, along with the constant supervision of the algorithm's performance, are critical to check for such bias and inequality (Mensah, 2023). Applying ethnographic studies, data scientists, and healthcare professionals, among other parties, can promote equitable AI (Katell et al., 2020).

In conclusion, AI has high potential to transform virus infection research and enhance the world's health care. However, there are several concerns that must be overcome: data privacy, security, and bias. Ensuring effective measures of data protection and enforcing fairness during the development of AI models, it is possible to realize the potential of AI while respecting ethical norms and individual rights

4. Future Perspectives and Recommendations

With the advancement of virus infection studies with the help of AI integration and the basic measures being taken worldwide, the following areas should be given importance to get the maximum benefits to address the existing pitfalls. Based on these considerations, the priorities for future works and recommendations are cooperation in data sharing and dissemination, in enhancing the process of building common methods for collecting and measuring big data, and in the ethical issue regarding the application of AI solutions.

4.1. Collaborative Efforts for Data Sharing: Cooperative data exchange is essential for enhancing AI's impact on health sciences. Integrating data from various institutions, countries, and disciplines can contribute to creating extensive datasets that would enhance AI models' efficiency and reliability. For example, during the COVID-19 pandemic, collaborations in discovering and sharing data on the virus and the variant strains became possible. Combining multiple datasets from various countries could be possible by forming IDCs and signing data-sharing contracts; however, several precautions, like strict access control measures and anonymization methods, should be adopted to prevent the misuse of the same data.

4.2. Standardization of Data Collection Methods: The consistency of data collection instruments for various studies is essential in enhancing the quality and compatibility of health data in AI studies. It is important to consistently format data, measure the same

thing, and report data similarly to enable its integration and analysis. Standard operating procedures about data capturing and reporting like patient details, diagnostic findings, and treatment outcomes can help in the compatibility and comparing of data across different healthcare facilities and research projects. The action of the regulatory bodies, professional associations, and international health organizations plays a vital role in promoting universal acceptance and adherence to the guidelines.

4.3. Ethical Guidelines for AI Implementation: It is strategically crucial to set ethical standards to address the ethical issues of AI and its proper functioning in health research and public health interventions. These guidelines should consider elements such as data protection, consent, openness, responsibility, and non-discrimination. Privacy and the safety of individuals' information must be a priority with outlined procedures on how data is utilized, stored, and disseminated. Consent procedures must be clear so that people know how their data will be used and what risks were adopted

Additionally, AI's source codes and decision-making procedures must be transparent so external parties can review the firm's actions. These tools should be put in place to avoid undesirable effects or prejudice that may result from the use of AI. Conducting annual audits, periodic impact assessments, and the participation of multidisciplinary ethics committees would guide the creation and implementation of AI systems that do not compromise society's ethical standards.

In summary, the development of AI in virus infection and global health applications depends on open data sharing, evolving consistent data collection methodologies, and strong ethical frameworks. Thus, addressing these key areas will improve the efficiency, robustness, and ethical standards of AI interventions, increase health system performance, and contribute to health improvements worldwide.

5. The Summary of the Review

Introduction and Overview Artificial Intelligence (AI) has established itself as an essential tool for advancing the knowledge and management of infectious diseases caused by a broad range of pathogens, including bacteria, viruses, fungi, and parasites. Infectious diseases are one of the broad clinical threats to public health worldwide, often causing disastrous outbreaks and pandemics, such as those witnessed during COVID-19, SARS, and influenza epidemics. Early diagnosis and accurate treatment are crucial in controlling such infections. Though enormous progress is witnessed in the traditional approaches, these methods are slow in processing large complex datasets created through modern healthcare and research. AI can enhance these processes by providing quick identification of trends, breakout, and optimum treatment strategies through its capabilities of data analysis, machine learning, and predictive modelling. It is also important to note that the use of AI is not limited to diagnostic tools for viral research; it is also involved in drug discovery, genetic mapping, and population modelling. The three types of learning algorithms, supervised, unsupervised and deep learning, are effective in medical imaging analysis, biomarker detection and disease prognosis. The implementation of AI within the handling of the healthcare sector has improved the assessments of the risks that are likely to affect the population and respond rapidly to them. However, the implementation of AI in this field has challenges, such as data privacy, algorithmic bias, and ethical issues. It is crucial to address such problems through enhanced data sharing, methodological consistency, and stringent ethical framework to unlock AI capabilities in the prevention and treatment of viral diseases for the overall betterment of human health.

7.1 Results: The findings of the research show that AI is a tool that has significantly affected many aspects of viral infection work, including target discovery for drugs, disease mapping, vaccine creation, epidemiological studies, and testing.

7.2 Therapeutic Target Identification: AI has been described to be helpful in the prediction of possible therapeutic targets for multiple viral diseases such as the current SARS-CoV-2, HIV, and Influenza. Deep learning algorithms and molecular docking techniques have facilitated the high throughput screening and identification of viral proteins and host factors that can act as drug targets. The integration of AI in molecular dynamics simulation has further improved its goals, whereby structural analysis of viral proteins leads to the formulation of more potent antiviral drugs. The results also confirm the ability of AI-based models to decrease the time for drug discovery as potentially effective solutions are excluded at the start of the developments, making the process faster.

7.3 Data Mining and Predictive Modelling: The research concluded that many algorithms like machine learning Random forests, Decision trees, and Neural Networks have been beneficial in the interpretation of large-scale clinical and epidemiological databases. These models have been applied in the cases of infection rate prediction, risky population detection, and accurate classification of disease phases. Through the inclusion of patient-based demographics and genetic-based data, as well as environmental and weather data, AI has been able to improve the accuracy of outbreak prediction and promote real-time response. AI models in decision-making concerning resources have also been effective in situations in which healthcare facilities experience an increased influx of patients.

7.4 Vaccine Development: An area that has received much attention regarding the adoption of AI in viral research is the production of vaccines. The findings show that AI algorithms have been used to speed up the process of developing efficient vaccines in predicting immunogenic epitopes, optimizing mRNA sequences, and modelling immune responses. Current forms of antigen prediction using machine learning techniques have recently been used to predict potential vaccinations for several viral infections, including COVID-19, Zika virus and Influenza. The application of artificial intelligence in the initial phase of the vaccine development process has ensured the quick development of vaccines through a more efficient containment of viral threats.

7.5 Epidemiological Modelling: Some mobility data analyses and applications of network analysis are used to simulate the flow of viral infections. Many structural models have given insight into how these viruses go through people and measures like social distance, contact tracing, and vaccinations. This study reveals the ways in which AI can improve even the projections of epidemiological patterns, which in many countries have been vital to guiding policy-making during pandemics. Optimal use of real-time data has been coupled with AI models to identify areas within a region that are likely to experience an outbreak and monitor the development of the variants.

7.6 Diagnostics: AI integration in diagnostics has significantly enhanced the means of identifying viral infections. Computer-aided diagnostic tools such as CNNs exhibit great potential in interpreting radiological data and diagnosing signs associated with viral infection in chest X-rays and CT scans. The findings indicate that the adoption of AI has made diagnosis more accessible, fast and effective, and patients benefited by having early signs of infections detected. Further, AI-diagnostic has been incorporated into point-of-care devices also to make diagnostics available and convenient in low-resource settings and healthcare delivery.

6. Conclusion

The article highlighted the potential of integrating AI with molecular research to improve understanding of virus infections, epidemiology, and preventive health measures. AI can accelerate therapeutic development, optimize vaccine strategies, and predict outbreaks more accurately. However, ethical concerns like data privacy and algorithmic bias need to be addressed. Collaboration among researchers, policymakers, and technology developers is crucial for maximizing AI's benefits and mitigating viral infection impact. Combining computational, multi-omics, and experimental techniques can lead to new therapeutic hypotheses. The findings of this review suggested that the combination of AI with molecular biology can become a breakthrough in the area of virus infection. Through the possibility of discovering new drugs quickly and navigating the best approach to creating vaccines and developing diagnostics, AI could help make public health responses faster and more robust. However, AI can only be used effectively if we overcome current problems regarding data quality, ethical issues, and prejudices of Artificial Intelligence.

7. Recommendations

8.1 Enhance Data Sharing and Collaboration: The study suggests that organizations involved in research, healthcare, and government should enhance collaboration to increase the availability of high-quality datasets. Strategic specifications of data sharing, in combination with solid data anonymization approaches, enable the development of more extensive data sets that support reliable AI models. This will require greater collaboration between academics, industry, and governments to overcome issues of data lockers and ultimately advance the use of AI within global health programs.

8.2 Standardize Data Collection and Reporting: The use of a standard procedural format in the collection of data and reporting is also crucial to avoid compromises between various research studies. To overcome the limitations mentioned earlier, the study

recommends the following approaches to standardization for data acquisition, processing and annotation. This approach will increase the compatibility of datasets so that they can be easily integrated with the AI models and make the results reproducible.

8.3 Develop Ethical Guidelines for AI Use: Considering the reasonably sensitive question of AI application in healthcare, the study calls for the development of comprehensive ethics, which could cover topics like data privacy, the innate tendency of the algorithms to be biased, or lack of transparency. This makes the proposed helpful approach in helping ethics committees with multidisciplinary experience in virus research to regularly audit AI applications and evaluate the impact of such applications in producing health benefits while avoiding risks to patients.

8.4 Focus on Bias Mitigation in AI Models: The review also highlighted the need to monitor the models periodically to consider the bias that affects their performance. Training on diverse populations, engaging minorities, labelling them fairly, and using additional fairness checks also help to eliminate many biases and improve the applicability of AI technologies in different healthcare facilities.

8.9 Invest in AI for Early Detection and Surveillance: To summarize, the study prescribes that the existing funding should be directed towards the creation of AI-based monitoring assets that could identify the early signs of any new viral strain. Through the use of such algorithms and state information from multiple sources, these tools can develop a forecast on an upcoming outbreak and, therefore, allow timely public health measures to be taken against future pandemics.

References

- Adeyemi, M. O., Oluyo, T. O., & Oladejo, J. K. (2020). Modelling the transmission and control dynamics of coronavirus disease with social distancing and contact tracing. International Journal of Innovative Science and Research Technology, 5(5), 948-964 .
- Agrebi, S., & Larbi, A. (2020). Use of artificial intelligence in infectious diseases. In Artificial intelligence in precision health (pp. 415-438). Elsevier .
- Albahri, A. S., Hamid, R. A., Alwan, J. K., Al-Qays, Z., Zaidan, A., Zaidan, B., Albahri, A., AlAmoodi, A. H., Khlaf, J. M., & Almahdi, E. (2020). Role of biological data mining and machine learning techniques in detecting and diagnosing the novel coronavirus (COVID-19): a systematic review. Journal of medical systems, 44, 1-11 .
- Aliper, A., Plis, S., Artemov, A., Ulloa, A., Mamoshina, P., & Zhavoronkov, A. (2016). Deep learning applications for predicting pharmacological properties of drugs and drug repurposing using transcriptomic data. Molecular pharmaceutics, 13(7), 2524-2530 .
- Alomar, O., Batlle, A., Brunetti, J., García, R., Gil, R., Granollers, A., Jiménez, S., Laviña, A., Linge, J., & Pautasso, M. (2015). Development and testing of the media monitoring tool med is ys for early identification and reporting of existing and emerging plant health threats. EPPO Bulletin, 45(2), 288-293 .
- Andry, J. F., Tannady, H., Dwinoor Rembulan, G., & Freggy Dinata, D. (2023). Analysis of the Omicron virus cases using data mining methods in rapid miner applications. Microbes and Infectious Diseases, 4(2), 323-334 .
- Arora, N., Banerjee, A. K., & Narasu, M. L. (2020). The role of artificial intelligence in tackling COVID-19. In (Vol. 15, pp. 717-724): Future Medicine.
- Available:, Y. T. O. (2020). Could fitness wearables help detect early signs of
- COVID-19? https://www.bostonmagazine.com/health/2020/04/03/tnesswearablescoro%navirus/
- Bagabir, S. A., Ibrahim, N. K., Bagabir, H. A., & Ateeq, R. H. (2022). Covid-19 and Artificial Intelligence: Genome sequencing, drug development and vaccine discovery. Journal of Infection and Public Health, 15(2), 289-296 .
- Bai, H. X., Hsieh, B., Xiong, Z., Halsey, K., Choi, J. W., Tran, T. M. L., Pan, I., Shi, L.-B., Wang, D.-C., & Mei, J. (2020). Performance of radiologists in differentiating COVID-19 from non-COVID-19 viral pneumonia at chest CT. Radiology, 296(2), E46-E54 .

- Baltrusaitis, K., Reed, C., Sewalk, K., Brownstein, J. S., Crawley, A. W., & Biggerstaff, M. (2022). Healthcare-seeking behavior for respiratory Illness among Flu Near you participants in the United States during the 2015–2016 through 2018–2019 Influenza Seasons. The Journal of Infectious Diseases, 226(2), 270-277 .
- Banerjee, A., Ray, S., Vorselaars, B., Kitson, J., Mamalakis, M., Weeks, S., Baker, M., & Mackenzie, L. S. (2020). Use of machine learning and artificial intelligence to predict SARS-CoV-2 infection from full blood counts in a population. International immunopharmacology, 86, 106705 .
- Bansal, A., Padappayil, R. P., Garg, C., Singal, A., Gupta, M., & Klein, A. (2020). Utility of artificial intelligence amidst the COVID 19 pandemic: a review. Journal of Medical Systems, 44, 1-6 .
- Berche, P. (2022). The Spanish flu. La Presse Médicale, 51(3), 104127 .
- Berryhill, S., Morton, C. J., Dean, A., Berryhill, A., Provencio-Dean, N., Patel, S. I., Estep, L., Combs, D., Mashaqi, S., & Gerald, L. B. (2020). Effect of wearables on sleep in healthy individuals: a randomized crossover trial and validation study. Journal of Clinical Sleep Medicine, 16(5), 775-783 .
- Bhattacharyya, S. (2021). Intelligent modeling, prediction, and diagnosis from epidemiological data: COVID-19 and beyond. CRC Press .
- Bohr, A., & Memarzadeh, K. (2020). The rise of artificial intelligence in healthcare applications. In Artificial Intelligence in healthcare (pp. 25-60). Elsevier .
- Bullock, J., Luccioni, A., Pham, K. H., Lam, C. S. N., & Luengo-Oroz, M. (2020). Mapping the landscape of artificial intelligence applications against COVID-19. Journal of Artificial Intelligence Research, 69, 807-845 .
- Carracedo-Reboredo, P., Liñares-Blanco, J., Rodríguez-Fernández, N., Cedrón, F., Novoa, F. J., Carballal, A., Maojo, V., Pazos, A., & Fernandez-Lozano, C. (2021). A review on machine learning approaches and trends in drug discovery. Computational and structural biotechnology journal, 19, 4538-4558 .
- Carrion, M., & Madoff, L. C. (2017). ProMED-mail: 22 years of digital surveillance of emerging infectious diseases. International health, 9(3), 177-183 .
- Castro, D., & New, J. (2016). The promise of artificial intelligence. Center for data innovation, 115(10), 32-35 .
- Chamola, V., Hassija, V., Gupta, V., & Guizani, M. (2020). A comprehensive review of the COVID-19 pandemic and the role of IoT, drones, AI, blockchain, and 5G in managing its impact. Ieee access, 8, 90225-90265 .
- Chumachenko, D., Meniailov, I., Bazilevych, K., Chumachenko, T., & Yakovlev, S. (2022). Investigation of statistical machine learning models for COVID-19 epidemic process simulation: Random forest, K-nearest neighbors, gradient boosting. Computation, 10(6), 86 .
- Colubri, A., Silver, T., Fradet, T., Retzepi, K., Fry, B., & Sabeti, P. (2016). Transforming clinical data into actionable prognosis models: machine-learning framework and field-deployable app to predict outcome of Ebola patients. PLoS neglected tropical diseases, 10(3), e0004549 .
- Cotugno, N., Santilli, V., Pascucci, G. R., Manno, E. C., De Armas, L., Pallikkuth, S., Deodati, A., Amodio, D., Zangari, P., & Zicari, S. (2020). Artificial intelligence applied to in vitro gene expression testing (IVIGET) to predict trivalent inactivated influenza vaccine immunogenicity in HIV infected children. Frontiers in immunology, 11, 559590 .
- Dash, T. K., Chakraborty, C., Mahapatra, S., & Panda, G. (2022). Gradient boosting machine and efficient combination of features for speech-based detection of COVID-19. IEEE Journal of Biomedical and Health Informatics, 26(11), 5364-5371 .
- Dion, M., AbdelMalik, P., & Mawudeku, A. (2015). Big data: big data and the global public health intelligence network (GPHIN). Canada communicable disease report, 41(9), 209 .
- Dlugatch, R., Georgieva, A., & Kerasidou, A. (2023). Trustworthy artificial intelligence and ethical design: public perceptions of trustworthiness of an AI-based decision-support tool in the context of intrapartum care. BMC Medical Ethics, 24(1), 42 .

- Eames, K. T., & Keeling, M. J. (2003). Contact tracing and disease control. Proceedings of the Royal Society of London. Series B: Biological Sciences, 270(1533), 2565-2571 .
- Ekins, S., Freundlich, J. S., Clark, A. M., Anantpadma, M., Davey, R. A., & Madrid, P. (2015). Machine learning models identify molecules active against the Ebola virus in vitro. F1000Research, 4 .
- Ekpenyong, M. E., Uzoka, F.-M., Edoho, M., Inyang, U. G., Udo, I. J., Uto, N. P., Ekaidem, I. S., Moses, A. E., Anwana, E. D., & Tatfeng, Y. M. (2021). Real Time Viral Sub-Strains Discovery in Emerging Infectious Disease Situation—The African Perspective .
- Fair, J. M., LeClaire, R. J., Dauelsberg, L. R., Ewers, M., Pasqualini, D., Cleland, T., & Rosenberger, W. (2021). Systems dynamics and the uncertainties of diagnostics, testing and contact tracing for COVID-19. Methods, 195, 77-91 .
- Fang, X., Liu, W., Ai, J., He, M., Wu, Y., Shi, Y., Shen, W., & Bao, C. (2020). Forecasting incidence of infectious diarrhea using random forest in Jiangsu Province, China. BMC infectious diseases, 20, 1-8 .
- Favour, O., & Potter, K. (2024). The Future of AI in Public Health: Unlocking Opportunities and Addressing Challenges .
- Fazelpour, S., & Danks, D. (2021). Algorithmic bias: Senses, sources, solutions. Philosophy Compass, 16(8), e12760 .
- Finkbeiner, S. (2024). Deep learning and deep phenotyping of HD iPSCs: Applications to study biology and test therapeutics. In Huntington's Disease (pp. 473-498). Elsevier .
- Fletcher, R. R., Nakeshimana, A., & Olubeko, O. (2021). Addressing fairness, bias, and appropriate use of artificial intelligence and machine learning in global health. In (Vol. 3, pp. 561802): Frontiers Media SA.
- Fraley, S. I., Athamanolap, P., Masek, B. J., Hardick, J., Carroll, K. C., Hsieh, Y.-H., Rothman, R. E., Gaydos, C. A., Wang, T.-H., & Yang, S. (2016). Nested machine learning facilitates increased sequence content for large-scale automated high resolution melt genotyping. Scientific reports, 6(1), 19218 .
- Frias, M., Moyano, J. M., Rivero-Juarez, A., Luna, J. M., Camacho, Á., Fardoun, H. M., Machuca, I., Al-Twijri, M., Rivero, A., & Ventura, S. (2021). Classification accuracy of hepatitis C virus infection outcome: data mining approach. Journal of Medical Internet Research, 23(2), e18766 .
- Ganser, I., Thiébaut, R., & Buckeridge, D. L. (2022). Global variations in event-based surveillance for disease outbreak detection: time series analysis. JMIR Public Health and Surveillance, 8(10), e36211 .
- Gao, K., Wang, R., Chen, J., Cheng, L., Frishcosy, J., Huzumi, Y., Qiu, Y., Schluckbier, T., Wei, X., & Wei, G.-W. (2022). Methodology-centered review of molecular modeling, simulation, and prediction of SARS-CoV-2. Chemical Reviews, 122(13), 11287-11368 .
- Ge, Q., Lu, X., Jiang, R., Zhang, Y., & Zhuang, X. (2024). Data mining and machine learning in HIV infection risk research: An overview and recommendations. Artificial Intelligence in Medicine, 102887 .
- Go, T., Kim, J. H., Byeon, H., & Lee, S. J. (2018). Machine learning-based in-line holographic sensing of unstained malaria-infected red blood cells. Journal of biophotonics, 11(9), e201800101 .
- Guidance, W. (2021). Ethics and governance of artificial intelligence for health. World Health Organization .
- Guirao, A. (2020). The Covid-19 outbreak in Spain. A simple dynamics model, some lessons, and a theoretical framework for control response. Infectious Disease Modelling, 5, 652-669 .
- Gulyaeva, M., Huettmann, F., Shestopalov, A., Okamatsu, M., Matsuno, K., Chu, D.-H., Sakoda, Y., Glushchenko, A., Milton, E., & Bortz, E. (2020). Data mining and model-predicting a global disease reservoir for low-pathogenic Avian Influenza (AI) in the wider pacific rim using big data sets. Scientific reports, 10(1), 16817 .
- Habuza, T., Navaz, A. N., Hashim, F., Alnajjar, F., Zaki, N., Serhani, M. A., & Statsenko, Y. (2021). AI applications in robotics, diagnostic image analysis and precision medicine: Current limitations, future trends, guidelines on CAD systems for medicine. Informatics in Medicine Unlocked, 24, 100596 .

- Haleem, A., Javaid, M., & Vaishya, R. (2020). Effects of COVID-19 pandemic in daily life. Current medicine research and practice, 10(2), 78 .
- Harris, J. K., Hinyard, L., Beatty, K., Hawkins, J. B., Nsoesie, E. O., Mansour, R., & Brownstein, J. S. (2018). Evaluating the implementation of a twitter-based foodborne illness reporting tool in the city of St. Louis department of health. International journal of environmental research and public health, 15(5), 833 .
- Hassija, V., Chamola, V., Saxena, V., Jain, D., Goyal, P., & Sikdar, B. (2019). A survey on IoT security: application areas, security threats, and solution architectures. Ieee access, 7, 82721-82743 .
- Hawkins, J. B., Tuli, G., Kluberg, S., Harris, J., Brownstein, J. S., & Nsoesie, E. (2016). A digital platform for local foodborne illness and outbreak surveillance. Online Journal of Public Health Informatics, 8 .(1)
- Hayami, A. (2015). The Influenza Pandemic in Japan, 1918–1920: The First World War between Humankind and a Virus. The Influenza Pandemic in Japan, 1918–1920: The First World War between Humankind and a Virus .
- Hiremath, S., Yang, G., & Mankodiya, K. (2014). Wearable Internet of Things: Concept, architectural components and promises for person-centered healthcare. 2014 4th International Conference on Wireless Mobile Communication and Healthcare-Transforming Healthcare Through Innovations in Mobile and Wireless Technologies (MOBIHEALTH) ,
- Hopkins, J. (2020). COVID-19 map-johns Hopkins coronavirus resource center. Johns Hopkins Coronavirus Resource Center, 1 .
- Hosny, A., Parmar, C., Quackenbush, J., Schwartz, L. H., & Aerts, H. J. (2018). Artificial intelligence in radiology. Nature Reviews Cancer, 18(8), 500-510 .
- Hu, Z., Ge, Q., Li, S., Jin, L., & Xiong, M. (2020). Artificial intelligence forecasting of covid-19 in china. arXiv preprint arXiv:2002.07112 .
- Huang, C.-J., Chen, Y.-H., Ma, Y., & Kuo, P.-H. (2020). Multiple-input deep convolutional neural network model for covid-19 forecasting in china. MedRxiv, 2020.2003. 2023.20041608 .
- Huang, X. (2020). Application analysis of AI reasoning engine in microblog culture industry. Personal and Ubiquitous Computing, 24(3), 393-403 .
- Ibrahim, A. U., Ozsoz, M., Serte, S., Al-Turjman, F., & Yakoi, P. S. (2021). Pneumonia classification using deep learning from chest X-ray images during COVID-19. Cognitive Computation, 1-13 .
- Indrakumari, R., Poongodi, T., Suresh, P., & Balamurugan, B. (2020). The growing role of Internet of Things in healthcare wearables. In Emergence of Pharmaceutical Industry Growth with Industrial IoT Approach (pp. 163-194). Elsevier .
- Injadat, M., Moubayed, A., Nassif, A. B., & Shami, A. (2021). Machine learning towards intelligent systems: applications, challenges, and opportunities. Artificial Intelligence Review, 54(5), 3299-3348 .
- Jabour, A. M., Varghese, J., Damad, A. H., Ghailan, K. Y., & Mehmood, A. M. (2021). Examining the correlation of google influenza trend with hospital data: retrospective study. Journal of Multidisciplinary Healthcare, 3073-3081 .
- Jenner, A. L., Aogo, R. A., Davis, C. L., Smith, A. M., & Craig, M. (2020). Leveraging computational modeling to understand infectious diseases. Current Pathobiology Reports, 8, 149-161 .
- Jiang, X., Coffee, M., Bari, A., Wang, J., Jiang, X., Huang, J., Shi, J., Dai, J., Cai, J., & Zhang, T. (2020). Towards an artificial intelligence framework for data-driven prediction of coronavirus clinical severity. Computers, Materials & Continua, 63(1), 537-551 .
- Kadhim, Q. K. (2017). Classification of human skin diseases using data mining. International Journal of Advanced Engineering Research and Science, 4(1), 237008 .
- Kane, M. J., Price, N., Scotch, M., & Rabinowitz, P. (2014). Comparison of ARIMA and Random Forest time series models for prediction of avian influenza H5N1 outbreaks. BMC bioinformatics, 15, 1-9 .

- Kangabam, R., Sahoo, S., Ghosh, A., Roy, R., Silla, Y., Misra, N., & Suar, M. (2021). Next-generation computational tools and resources for coronavirus research: From detection to vaccine discovery. Computers in biology and medicine, 128, 104158 .
- Kara, A. (2021). Multi-step influenza outbreak forecasting using deep LSTM network and genetic algorithm. Expert Systems with Applications, 180, 115153 .
- Kasamatsu, A., Ota, M., Shimada, T., Fukusumi, M., Yamagishi, T., Samuel, A., Nakashita, M., Ukai, T., Kurosawa, K., & Urakawa, M. (2021). Enhanced event-based surveillance for imported diseases during the Tokyo 2020 Olympic and Paralympic Games. Western Pacific Surveillance and Response Journal: WPSAR, 12(4), 1 .
- Katell, M., Young, M., Dailey, D., Herman, B., Guetler, V., Tam, A., Bintz, C., Raz, D., & Krafft, P. (2020). Toward situated interventions for algorithmic equity: lessons from the field. Proceedings of the 2020 conference on fairness, accountability, and transparency ,
- Kaushik, A. K., Dhau, J. S., Gohel, H., Mishra, Y. K., Kateb, B., Kim, N.-Y., & Goswami, D. Y. (2020). Electrochemical SARS-CoV-2 sensing at point-of-care and artificial intelligence for intelligent COVID-19 management. ACS Applied Bio Materials, 3(11), 7306-7325 .
- Kavadi, D. P., Patan, R., Ramachandran, M., & Gandomi, A. H. (2020). Partial derivative nonlinear global pandemic machine learning prediction of covid 19. Chaos, Solitons & Fractals, 139, 110056 .
- Kebede, M., Zegeye, D. T., & Zeleke, B. M. (2017). Predicting CD4 count changes among patients on antiretroviral treatment: Application of data mining techniques. Computer methods and programs in biomedicine, 152, 149-157 .
- Khemasuwan, D., Sorensen, J. S., & Colt, H. G. (2020). Artificial intelligence in pulmonary medicine: computer vision, predictive model and COVID-19. European respiratory review, 29 .(157)
- Klongthong, W., Muangsin, V., Gowanit, C., & Muangsin, N. (2020). Chitosan biomedical applications for the treatment of viral disease: a data mining model using bibliometric predictive intelligence. Journal of Chemistry, 2020, 1-12 .
- Kwok, K. O., Tang, A., Wei, V. W., Park, W. H., Yeoh, E. K., & Riley, S. (2019). Epidemic models of contact tracing: systematic review of transmission studies of severe acute respiratory syndrome and middle east respiratory syndrome. Computational and structural biotechnology journal, 17, 186-194 .
- Lee, D., & Yoon, S. N. (2021). Application of artificial intelligence-based technologies in the healthcare industry: Opportunities and challenges. International journal of environmental research and public health, 18(1), 271 .
- Liao, H.-C., & Tsai, J.-H. (2007). Data mining for DNA viruses with breast cancer, fibroadenoma, and normal mammary tissue. Applied mathematics and computation, 188(1), 989-1000 .
- Ling-Hu, T., Rios-Guzman, E., Lorenzo-Redondo, R., Ozer, E. A., & Hultquist, J. F. (2022). Challenges and opportunities for global genomic surveillance strategies in the COVID-19 era. Viruses, 14(11), 2532 .
- Linge, J. P., Steinberger, R., Fuart, F., Bucci, S., Belyaeva, J., Gemo, M., Al-Khudhairy, D., Yangarber, R., & van der Goot, E. (2010). MedISys: medical information system. In Advanced ICTs for disaster management and threat detection: Collaborative and distributed frameworks (pp. 131-142). IGI Global .
- Luo, W., Nguyen, T., Nichols, M., Tran, T., Rana, S., Gupta, S., Phung, D., Venkatesh, S., & Allender, S. (2015). Is demography destiny? Application of machine learning techniques to accurately predict population health outcomes from a minimal demographic dataset. PloS one, 10(5), e0125602 .
- M, H. (2020). "COVID-19: AI can help but the right human input is
- key," World Economic Forum, Mar. 2020. . https://www.weforum.org/agenda/2020/03/covid-19-crisisarticialintel%ligence-creativity/
- M., R. (2015). What is IoMT (Internet of Medical Things) or healthcare
- IoT: definition from WhatIs.com .

- Maharjan, R., Hada, S., Lee, J. E., Han, H.-K., Kim, K. H., Seo, H. J., Foged, C., & Jeong, S. H. (2023). Comparative study of lipid nanoparticle-based mRNA vaccine bioprocess with machine learning and combinatorial artificial neural network-design of experiment approach. International Journal of Pharmaceutics, 640, 123012 .
- Majumdar, A., Debnath, T., Sood, S. K., & Baishnab, K. L. (2018). Kyasanur forest disease classification framework using novel extremal optimization tuned neural network in fog computing environment. Journal of medical systems, 42, 1-16 .
- Mak, K.-K., Wong, Y.-H., & Pichika, M. R. (2023). Artificial intelligence in drug discovery and development. Drug Discovery and Evaluation: Safety and Pharmacokinetic Assays, 1-38 .
- Malki, Z., Atlam, E.-S., Ewis, A., Dagnew, G., Alzighaibi, A. R., ELmarhomy, G., Elhosseini, M. A., Hassanien, A. E., & Gad, I. (2021). ARIMA models for predicting the end of COVID-19 pandemic and the risk of second rebound. Neural Computing and Applications, 33, 2929-2948 .
- Malone, B., Simovski, B., Moliné, C., Cheng, J., Gheorghe, M., Fontenelle, H., Vardaxis, I., Tennøe, S., Malmberg, J.-A., & Stratford, R. (2020). Artificial intelligence predicts the immunogenic landscape of SARS-CoV-2 leading to universal blueprints for vaccine designs. Scientific reports, 10(1), 22375 .
- Mamalakis, M., Swift, A. J., Vorselaars, B., Ray, S., Weeks, S., Ding, W., Clayton, R. H., Mackenzie, L. S., & Banerjee, A. (2021). DenResCov-19: A deep transfer learning network for robust automatic classification of COVID-19, pneumonia, and tuberculosis from X-rays. Computerized Medical Imaging and Graphics, 94, 102008 .
- Mamoshina, P., Ojomoko, L., Yanovich, Y., Ostrovski, A., Botezatu, A., Prikhodko, P., Izumchenko, E., Aliper, A., Romantsov, K., & Zhebrak, A. (2018). Converging blockchain and next-generation artificial intelligence technologies to decentralize and accelerate biomedical research and healthcare. Oncotarget, 9(5), 5665 .
- Mateus-Coelho, N., & Cruz-Cunha, M. (2023). Exploring Cyber Criminals and Data Privacy Measures. IGI Global .
- Meganck, R. M., & Baric, R. S. (2021). Developing therapeutic approaches for twenty-first-century emerging infectious viral diseases. Nature medicine, 27(3), 401-410 .
- Mensah, G. B. (2023). Artificial Intelligence and Ethics: A Comprehensive Review of Bias Mitigation, Transparency, and Accountability in AI Systems. In: November.
- Minssen, T., Seitz, C., Aboy, M., & Compagnucci, M. C. (2020). The EU-US Privacy Shield Regime for Cross-Border Transfers of Personal Data under the GDPR: What are the legal challenges and how might these affect cloud-based technologies, big data, and AI in the medical sector? EPLR, 4, 34 .
- Misra, B. B., Langefeld, C., Olivier, M., & Cox, L. A. (2019). Integrated omics: tools, advances and future approaches. Journal of molecular endocrinology, 62(1), R21-R45 .
- Mottaqi, M. S., Mohammadipanah, F., & Sajedi, H. (2021). Contribution of machine learning approaches in response to SARS-CoV-2 infection. Informatics in Medicine Unlocked, 23, 100526 .
- Mouchlis, V. D., Afantitis, A., Serra, A., Fratello, M., Papadiamantis, A. G., Aidinis, V., Lynch, I., Greco, D., & Melagraki, G. (2021). Advances in de novo drug design: from conventional to machine learning methods. International journal of molecular sciences, 22(4), 1676 .
- Müller, J., & Kretzschmar, M. (2021). Contact tracing—old models and new challenges. Infectious Disease Modelling, 6, 222-231 .
- Naudé, W. (2020). Artificial Intelligence against COVID-19: An early review .
- Nazer, L. H., Zatarah, R., Waldrip, S., Ke, J. X. C., Moukheiber, M., Khanna, A. K., Hicklen, R. S., Moukheiber, L., Moukheiber, D., & Ma, H. (2023). Bias in artificial intelligence algorithms and recommendations for mitigation. PLOS digital health, 2(6), e0000278 .

- Nousi, C., Belogianni, P., Koukaras, P., & Tjortjis, C. (2022). Mining data to deal with epidemics: case studies to demonstrate real world AI applications. Handbook of Artificial Intelligence in Healthcare: Vol. 1-Advances and Applications, 287-312 .
- Olsen, L. R., Zhang, G. L., Reinherz, E. L., & Brusic, V. (2011). FLAVIdB: a data mining system for knowledge discovery in flaviviruses with direct applications in immunology and vaccinology. Immunome research, 7 .(3)
- Organization, W. H. (2015). WHO publishes list of top emerging diseases likely to cause major epidemics. Geneva: World Health Organization .
- Osmundsen, T. C., Andreassen Jaatun, E. A., Heggem, G. F., & Kulseng, B. E. (2015). Service innovation from the edges: enhanced by telemedicine decision support. Personal and Ubiquitous Computing, 19, 699-708 .
- Peng, J., Zou, K., Zhou, M., Teng, Y., Zhu, X., Zhang, F., & Xu, J. (2021). An explainable artificial intelligence framework for the deterioration risk prediction of hepatitis patients. Journal of medical systems, 45(5), 61 .
- Pinzi, L., & Rastelli, G. (2019). Molecular docking: shifting paradigms in drug discovery. International journal of molecular sciences, 20(18), 4331 .
- Pun, F. W., Ozerov, I. V., & Zhavoronkov, A. (2023). AI-powered therapeutic target discovery. Trends in Pharmacological Sciences .
- Qayyum, M. U., Sherani, A. M. K., Khan, M., Shiwlani, A., & Hussain, H. K. (2024). Using AI in Healthcare to Manage Vaccines Effectively. JURIHUM: Jurnal Inovasi dan Humaniora, 1(6), 841-854 .
- Radin, J. M., Wineinger, N. E., Topol, E. J., & Steinhubl, S. R. (2020). Harnessing wearable device data to improve state-level real-time surveillance of influenza-like illness in the USA: a population-based study. The Lancet Digital Health, 2(2), e85-e93 .
- Rando, H. M., Wellhausen, N., Ghosh, S., Lee, A. J., Dattoli, A. A., Hu, F., Byrd, J. B., Rafizadeh, D. N., Lordan, R., & Qi, Y. (2021). Identification and Development of Therapeutics for COVID-19. Msystems, 6(6), e00233-00221 .
- Rees, E., Ng, V., Gachon, P., Mawudeku, A., McKenney, D., Pedlar, J., Yemshanov, D., Parmely, J., & Knox, J. (2019). Early detection and prediction of infectious disease outbreaks. CCDR, 45 .(5)
- Reperant, L. A., & Osterhaus, A. D. (2017). AIDS, Avian flu, SARS, MERS, Ebola, Zika... what next? Vaccine, 35(35), 4470-4474 .
- Restif, O., & Graham, A. L. (2015). Within-host dynamics of infection: from ecological insights to evolutionary predictions. In (Vol. 370, pp. 20140304): The Royal Society.
- Richard, M., & Fouchier, R. A. (2016). Influenza A virus transmission via respiratory aerosols or droplets as it relates to pandemic potential. FEMS microbiology reviews, 40(1), 68-85 .
- Riley, S., Fraser, C., Donnelly, C. A., Ghani, A. C., Abu-Raddad, L. J., Hedley, A. J., Leung, G. M., Ho, L.-M., Lam, T.-H., & Thach, T. Q. (2003). Transmission dynamics of the etiological agent of SARS in Hong Kong: impact of public health interventions. Science, 300(5627), 1961-1966 .
- Rodrigues, J. J., Segundo, D. B. D. R., Junqueira, H. A., Sabino, M. H., Prince, R. M., Al-Muhtadi, J., & De Albuquerque, V. H. C. (2018). Enabling technologies for the internet of health things. Ieee access, 6, 13129-13141 .
- Saad, Y., Awad, A., Alakel, W., Doss, W., Awad, T., & Mabrouk, M. (2018). Data mining of routine laboratory tests can predict liver disease progression in Egyptian diabetic patients with hepatitis C virus (G4) infection: a cohort study of 71 806 patients. European journal of gastroenterology & hepatology, 30(2), 201-206 .
- Safdari, R., Deghatipour, A., Gholamzadeh, M., & Maghooli, K. (2022). Applying data mining techniques to classify patients with suspected hepatitis C virus infection. Intelligent Medicine, 2(04), 193-198 .
- Saleh, A. I., & Rabie, A. H. (2023). Human monkeypox diagnose (HMD) strategy based on data mining and artificial intelligence techniques. Computers in Biology and Medicine, 152, 106383 .
- Salehi, A. W., Baglat, P., & Gupta, G. (2020). Review on machine and deep learning models for the detection and prediction of Coronavirus. Materials Today: Proceedings, 33, 3896-3901 .

- Sareen, S., Gupta, S. K., & Sood, S. K. (2017). An intelligent and secure system for predicting and preventing Zika virus outbreak using Fog computing. Enterprise Information Systems, 11(9), 1436-1456 .
- Sarker, I. H. (2022). AI-based modeling: techniques, applications and research issues towards automation, intelligent and smart systems. SN Computer Science, 3(2), 158 .
- Saurabh, S., & Prateek, S. (2017). Role of contact tracing in containing the 2014 Ebola outbreak: a review. African health sciences, 17(1), 225-236 .
- Schmitt, M. (2020). How to fight COVID-19 with machine learning towards data science. Medium. Apr .
- Senior, A. W., Evans, R., Jumper, J., Kirkpatrick, J., Sifre, L., Green, T., Qin, C., Žídek, A., Nelson, A. W., & Bridgland, A. (2020). Improved protein structure prediction using potentials from deep learning. Nature, 577(7792), 706-710 .
- Shapiro, A., Marinsek, N., Clay, I., Bradshaw, B., Ramirez, E., Min, J., Trister, A., Wang, Y., Althoff, T., & Foschini, L. (2021). Characterizing COVID-19 and influenza illnesses in the real world via person-generated health data. Patterns, 2 .(1)
- Siddiq, M. (2023). Exploring the role of machine learning in contact tracing for public health: benefits, challenges, and ethical considerations. American Journal of Economic and Management Business (AJEMB), 2(3), 99-110 .
- Silver, D., Schrittwieser, J., Simonyan, K., Antonoglou, I., Huang, A., Guez, A., Hubert, T., Baker, L., Lai, M., & Bolton, A. (2017). Mastering the game of go without human knowledge. nature, 550(7676), 354-359 .
- Sim, S., & Cho, M. (2022). A study on Web service supporting mobility of users using ICT-based autonomous feedback knowledge information. Personal and Ubiquitous Computing, 26(2), 209-219 .
- Sim, S., & Cho, M. (2023). Convergence model of AI and IoT for virus disease control system. Personal and Ubiquitous Computing, 27(3), 1209-1219 .
- Singh, R. K., Rani, M., Bhagavathula, A. S., Sah, R., Rodriguez-Morales, A. J., Kalita, H., Nanda, C., Sharma, S., Sharma, Y. D., & Rabaan, A. A. (2020). Prediction of the COVID-19 pandemic for the top 15 affected countries: Advanced autoregressive integrated moving average (ARIMA) model. JMIR public health and surveillance, 6(2), e19115 .
- Sun, G., Matsui, T., Hakozaki, Y., & Abe, S. (2015). An infectious disease/fever screening radar system which stratifies higher-risk patients within ten seconds using a neural network and the fuzzy grouping method. Journal of Infection, 70(3), 230-236 .
- T., H. (2020). What America Can Learn From China's Use of Robots
- and Telemedicine to Combat the Coronavirus. . https://www.cnbc.com/2020/03/18/howchina-isusing-robots-and-telemedic%ine-to-combat-thecoronavirus.html
- Tarasova, O., Biziukova, N., Shemshura, A., Filimonov, D., Kireev, D., Pokrovskaya, A., & Poroikov, V. V. (2023). Identification of molecular mechanisms involved in viral infection progression based on text mining: case study for HIV infection. International Journal of Molecular Sciences, 24(2), 1465 .
- Tewari, A., & Gupta, B. B. (2020). Security, privacy and trust of different layers in Internet-of-Things (IoTs) framework. Future generation computer systems, 108, 909-920 .
- Thapa, C., & Camtepe, S. (2021). Precision health data: Requirements, challenges and existing techniques for data security and privacy. Computers in biology and medicine, 129, 104130 .
- Thomford, N. E., Senthebane, D. A., Rowe, A., Munro, D., Seele, P., Maroyi, A., & Dzobo, K. (2018). Natural products for drug discovery in the 21st century: innovations for novel drug discovery. International journal of molecular sciences, 19(6), 1578 .
- Topol, E. J. (2019). High-performance medicine: the convergence of human and artificial intelligence. Nature medicine, 25(1), 44-56 .
- Tzanou, M. (2023). Health Data Privacy Under the GDPR. TAYLOR FRANCIS Limited .
- Vaishya, R., Javaid, M., Khan, I. H., & Haleem, A. (2020). Artificial Intelligence (AI) applications for COVID-19 pandemic. Diabetes & Metabolic Syndrome: Clinical Research & Reviews, 14(4), 337-339 .

- Valentin, S., Lancelot, R., & Roche, M. (2020). Information retrieval for animal disease surveillance: a pattern-based approach .
- Walsh, M. G., Willem de Smalen, A., & Mor, S. M. (2017). Wetlands, wild Bovidae species richness and sheep density delineate risk of Rift Valley fever outbreaks in the African continent and Arabian Peninsula. PLoS neglected tropical diseases, 11(7), e0005756 .
- Wang, S., Kang, B., Ma, J., Zeng, X., Xiao, M., Guo, J., Cai, M., Yang, J., Li, Y., & Meng, X. (2021). A deep learning algorithm using CT images to screen for Corona Virus Disease (COVID-19). European radiology, 31, 6096-6104 .
- Wang, T., Nie, Z., Wang, R., Xu, Q., Huang, H., Xu, H., Xie, F., & Liu, X.-J. (2023). PneuNet: deep learning for COVID-19 pneumonia diagnosis on chest X-ray image analysis using Vision Transformer. Medical & Biological Engineering & Computing, 61(6), 1395-1408 .
- Wei, W., Jiang, J., Gao, L., Liang, B., Huang, J., Zang, N., Ning, C., Liao, Y., Lai, J., & Yu, J. (2017). A new hybrid model using an autoregressive integrated moving average and a generalized regression neural network for the incidence of tuberculosis in Heng County, China. The American Journal of Tropical Medicine and Hygiene, 97(3), 799 .
- Woolhouse, M., & Gaunt, E. (2007). Ecological origins of novel human pathogens. Critical reviews in microbiology, 33(4), 231-242 .
- Yanagawa, M., Lorenzo, J. C., Fukusumi, M., Shimada, T., Kasamatsu, A., Ota, M., Nakashita, M., Kobayashi, M., Yamagishi, T., & Samuel, A. (2022). Use of Epidemic Intelligence from Open Sources for global event-based surveillance of infectious diseases for the Tokyo 2020 Olympic and Paralympic Games. Western Pacific Surveillance and Response Journal: WPSAR, 13(3), 1 .
- Yang, H., Wang, L., Xu, Y., & Liu, X. (2023). CovidViT: a novel neural network with self-attention mechanism to detect Covid-19 through X-ray images. International journal of machine learning and cybernetics, 14(3), 973-987 .
- Yang, X., Yang, S., Li, Q., Wuchty, S., & Zhang, Z. (2020). Prediction of human-virus protein-protein interactions through a sequence embedding-based machine learning method. Computational and structural biotechnology journal, 18, 153-161 .
- Yu, V. L., & Madoff, L. C. (2004). ProMED-mail: an early warning system for emerging diseases. Clinical infectious diseases, 39(2), 227-232 .
- Zhavoronkov, A., Ivanenkov, Y. A., Aliper, A., Veselov, M. S., Aladinskiy, V. A., Aladinskaya, A. V., Terentiev, V. A., Polykovskiy, D. A., Kuznetsov, M. D., & Asadulaev, A. (2019). Deep learning enables rapid identification of potent DDR1 kinase inhibitors. Nature biotechnology, 37(9), 1038-1040 .
- Zhou, S. K., Greenspan, H., Davatzikos, C., Duncan, J. S., Van Ginneken, B., Madabhushi, A., Prince, J. L., Rueckert, D., & Summers, R. M. (2021). A review of deep learning in medical imaging: Imaging traits, technology trends, case studies with progress highlights, and future promises. Proceedings of the IEEE, 109(5), 820-838 .

Theme of Sustainable Practices in Transportation and Mass Gatherings Management

Leveraging Autonomous-Rail Rapid Transit for Smart Mobility Solutions and Efficient Crowd Control in Almadinah Almunawarah

Hassan. A. Abas[*1], Omar Dakhil[2]

[1]*Civil Engineering Department, Prince Mugrin University

[2]Architecture Engineering Department, Prince Mugrin University

*Corresponding author: E-mail (h.abbas@upm.edu.sa)

الاستفادة من أنظمة النقل السريع الترددي ذاتي القيادة لتوفير حلول التنقل الذكية والتحكم الفعال في الحشود في المدينة المنورة

حس حسن علي*[1]، عمر الدخيل[2]

قسم الهندسة المدنية , جامعة الامير مقرن بن عبدالعزيز*[1]

قسم الهندسة المعمارية , جامعة الامير مقرن بن عبدالعزيز[2]

Abstract

Almadinah Almunawarah faces significant challenges in urban mobility and crowd management, particularly during peak periods like Hajj and Umrah, when millions of visitors overwhelm their transportation infrastructure. Traditional transit systems struggle to meet demand, leading to congestion, delays, and environmental concerns. This study proposes the implementation of an Autonomous-Rail Rapid Transit (ART) system as a sustainable solution. ART integrates autonomous driving technology with the efficiency of rail networks, offering a flexible, scalable option that requires minimal infrastructure investment. Unlike conventional rail systems, ART operates on virtual tracks, allowing rapid deployment and adaptation to fluctuating passenger demands. Additionally, the system's electric power and smart technologies, such as artificial intelligence and real-time data analytics, enhance operational efficiency and support effective crowd management. This research includes a review of ART systems, global case studies, and an analysis of Almadinah Almunawarah's transportation landscape, highlighting ART's potential to reduce congestion and improve transit performance. Although the study acknowledges challenges related to implementation, it concludes that ART aligns with the city's long-term development and sustainability goals. Recommendations include phased deployment, stakeholder collaboration, and investment strategies to ensure the system's successful adoption and seamless integration with existing infrastructure.

Keywords: Almadinah Almunawarah, Urban Mobility, Crowd Management, Autonomous-Rail Rapid Transit (ART), Sustainable Transportation, Hajj and Umrah

1. Introduction

Almadinah Almunawarah faces significant challenges in urban mobility and crowd management, especially during the annual influx of pilgrims for Hajj and Umrah. These religious events attract millions of visitors, placing massive pressure on the city's transportation infrastructure. As the number of pilgrims continues to rise, the existing transit systems struggle

to accommodate the growing demand, leading to severe traffic congestion and delays. The transportation network in Almadinah Almunawarah becomes overwhelmed during peak periods[1], [2]. Traditional public transit options, such as buses and taxis, often prove insufficient to efficiently manage the large influx of visitors. The resulting overcrowding on roads intensifies traffic bottlenecks, increasing travel times and contributing to elevated levels of pollution and environmental degradation. Additionally, the current infrastructure lacks the flexibility required to adapt to fluctuating passenger volumes during peak seasons. While temporary measures such as increasing bus frequency are employed, they are rarely enough to alleviate the long-term strain on the system. Consequently, the city needs a more scalable, adaptable solution that can not only address the current issues but also support future growth and sustainable urban development.

Autonomous-Rail Rapid Transit (ART) systems represent an innovative approach to urban transportation that combines the benefits of autonomous driving technology with the efficiency of rail networks [3], [4]. ART systems operate without human intervention, using advanced sensors, cameras, and artificial intelligence to navigate predetermined routes safely and efficiently[3]. Sunardi et al. (2022) reported that these systems eliminate the need for traditional infrastructure, such as rail tracks or overhead power lines, making them highly adaptable to existing urban environments [5]. The ART system offers versatile applications across multiple scenarios. It can support network connections and extensions for urban rail systems, serve as a backbone transportation system for small to medium-sized cities, and operate dedicated lines for tourist attractions or airport connections, among other uses [6].

Unlike conventional rail systems, ART offers greater flexibility in route planning and expansion. It operates on virtual tracks, which can be easily adjusted to accommodate changes in passenger demand or urban growth [7]. The autonomous technology embedded within ART allows for real-time decision-making, optimizing traffic flow and ensuring smooth operations even during periods of high congestion [8]. Han et al. (2020) reported that this strategy allows ART systems to detect obstacles (like pedestrians) and re-plan velocities in real time, reducing energy consumption by 36.21% and ensuring timely arrival at stations, even during congestion [9]. Moreover, ART integrates the precision and capacity of rail systems with the autonomous vehicle's ability to maneuver independently, creating a hybrid solution that maximizes both capacity and cost-effectiveness. The ART system's ability to combine autonomous driving and rail-like efficiency makes it a promising alternative for cities seeking scalable, sustainable transportation solutions.

Several cities around the world have successfully implemented ART systems, showcasing their potential as viable alternatives to traditional transit models. For instance, Zhuzhou in China has deployed ART to address urban congestion [4]. Beyond China's borders, the ART project is making strides, with endeavors in Kuching, Malaysia, and Abu Dhabi, poised for commercial operation by 2025. These examples demonstrate how ART can overcome the limitations of conventional transit systems by offering greater adaptability, scalability, and cost-efficiency, particularly in rapidly growing urban environments.

The primary objective of this study is to propose the implementation of an Autonomous-Rail Rapid Transit (ART) system as a practical solution for addressing the growing challenges of urban mobility and crowd management in Almadinah Almunawarah. The study intends to investigate how ART technology might improve transportation efficiency at peak periods, particularly during events such as Hajj and Umrah, when the city's transit infrastructure is severely challenged. In addition, the study examines ART's capability to optimize crowd control through its autonomous features, reducing

congestion while improving the overall passenger experience. This study is highly relevant to Almadinah Almunawarah's long-term goals of improving transportation efficiency and advancing sustainability.

2. Methodology

To assess the feasibility of an Autonomous-Rail Rapid Transit (ART) system in Almadinah Almunawarah , The methodology was divided into four phases: literature review, global case studies analysis, Almadinah Almunawarah transportation infrastructure assessment, and feasibility assessment for ART integration.

Phase 1: Literature Review and Technical Exploration: This phase began with an extensive literature review to understand ART's design, operational principles, and technological components, such as autonomous driving, virtual tracks, electric power integration, and AI-based operational efficiencies. Scholarly articles, and technical reports were examined to build a comprehensive understanding of ART's functional framework.

Phase 2: Global Case Studies: The phase examined case studies of cities, such as Zhuzhou and Yibin in China, which have successfully implemented ART systems to address urban transit challenges like congestion and limited space. These case studies provided insights into ART's deployment strategies, challenges encountered, and overall impact. The analysis focused on evaluating key performance metrics, including ridership, congestion reduction, infrastructure adaptability, and operational costs.

Phase 3: Almadinah Almunawarah's Transportation Infrastructure Analysis: This phase analyzed Almadinah Almunawarah's existing transportation infrastructure, particularly its ability to handle the large influx of visitors during peak seasons, such as Hajj and Umrah. This assessment included public transit systems, primarily buses and taxis, and their limitations. Data was collected through field surveys and document reviews. The analysis emphasized congestion hotspots, average transit times during peak and off-peak periods, and environmental impacts like carbon emissions.

Phase 4: Feasibility Assessment for ART Integration: This phase focused on assessing how an ART system could be integrated into Almadinah Almunawarah's transit landscape by evaluating several key aspects. First, the technical feasibility was examined to determine ART's ability to operate effectively in Almadinah Almunawarah's unique urban environment, particularly its compatibility with existing infrastructure. Next, the operational feasibility was assessed to understand the potential impact on current transit services, with an emphasis on reducing congestion and improving overall efficiency. Finally, the environmental impact was analyzed, highlighting the potential benefits such as reductions in carbon emissions and improvements in air quality. This environmental analysis was supported by data from similar implementations in other cities, adjusted specifically to fit the context of Almadinah Almunawarah.

3. Operational Principles of ART systems

Autonomous-Rail Rapid Transit (ART) systems feature multiple articulated, rubber-tire trams that rely on intelligent perception, path tracking, and trajectory-following technologies to operate without physical railway tracks. Figure 1 illustrates the core concepts of the ART system, while Table 1 presents key parameters of a three-module ART tram [4]. Unlike traditional rail systems, ART uses advanced sensors, GPS, and automated driving technologies to navigate along virtual paths, eliminating the need for fixed tracks. The bi-directional ART tram consists of multiple units, features a 100% low-floor design, and is powered entirely by electricity [4].

Table 1. Main parameters of the three-module ART tram[4]

Parameters Scale	Parameters Scale
Length/ m	31.64
Width/ m	2.65
Full load weight/t	54
Maximum number of passengers:	≥300 （AW3）
Maximum operating speed/(km·h-1)	70
Maximum sloping /%	10
Minimum turning radius/ m	15
Adaptability	100% Low-Deck

ART vehicles are typically designed to resemble modern trams or light rail units, offering multiple passenger compartments connected by articulated joints. This configuration ensures smoother turns and enhances maneuverability, especially in dense urban environments [10]. Additionally, modular design allows operators to adjust the vehicle length based on passenger demand, improving operational efficiency during peak and off-peak hours. Moreover, ART systems can operate seamlessly in mixed traffic, sharing roads with other vehicles, which eliminates the need for dedicated corridors [11]. This flexibility supports integration with existing urban infrastructure, enhancing the system's appeal for cities seeking sustainable transport solutions without extensive infrastructure overhauls.

Figure 1: The core concepts of the ART system.

The operational principles of ART systems focus on automation, connectivity, and safety. Autonomous driving technologies form the backbone of ART operations, using lidar, radar, and camera-based sensors to detect obstacles, monitor traffic conditions, and ensure safe navigation [12], [13]. These vehicles follow pre-defined virtual routes programmed into their control systems, adjusting their speeds dynamically in response to traffic flows. Another critical principle is vehicle-to-infrastructure (V2I) communication, which ensures that ART vehicles stay synchronized with traffic signals and road conditions [14], [15]. Through continuous data exchange, the system can optimize routes in real time, improving travel times and reducing energy consumption. In emergencies, ART systems can receive updates to reroute vehicles efficiently, ensuring operational continuity. Additionally, control centers continuously monitor vehicle performance and system operations, allowing for immediate intervention in the event of malfunctions or accidents.

4. Examining Global Case Studies of ART Implementation

Five major ART lines implemented globally are outlined in Table 1, highlighting their total lengths (in kilometers), number of stations, and operation start dates. The longest line, Harbin ART T1, extends 18.2 kilometers, while the shortest, Suzhou Wujiang ART MRT, spans 5.2 kilometers. These cities adopted ART strategically to alleviate traffic congestion and overcome spatial challenges, establishing themselves as pioneers in the field. Their experiences offer valuable insights into Almadinah Almunawarah's urban development, showing how ART can provide a sustainable transportation solution. These global projects illustrate the increasing adoption of ART as an innovative approach to public transit.

Table 2. Case Study of Key ART Implementations in China[4].

Line	City	Total Length (Km)	Number of Stations	Operation Start Date
Zhuzhou ART A1/A2 Line	Zhuzhou	14.5	19	2018
Yibin ART T1 Line	Yibin	17.7	17	2019
Harbin ART T1 Line	Harbin	18.2	7	2021
Suzhou Wujiang ART MRT Line	Suzhou	5.2	5	2021
Xi'an ART T1 Line	Xi'an	11.9	9	2023

5. Analysis of Almadinah Almunawarah's Current Transportation Infrastructure and Challenges

Almadinah Almunawarah's transportation infrastructure faces considerable strain, particularly during peak periods like Hajj and Umrah, when the city experiences a dramatic influx of visitors. The existing public transit network, consisting primarily of buses and taxis, often struggles to accommodate the heightened demand. As a result, transit services become overcome, leading to overcrowded vehicles, extended waiting times, and disruptions to scheduled operations.

This congestion creates a ripple effect, slowing the movement of traffic throughout the city and causing bottlenecks in key areas. The increased volume of vehicles not only prolongs travel times but also affects the efficiency of transport services, diminishing the overall quality of mobility. In addition to logistical challenges, environmental issues arise. Prolonged idling and stop-and-go traffic contribute to higher fuel consumption, increasing carbon emissions. These emissions, combined with the intensified movement of vehicles, elevate air pollution levels, raise concerns about the city's environmental sustainability. Addressing these challenges is essential to ensuring a functional, resilient transportation network. Without adequate solutions, Almadinah Almunawarah's mobility system will continue to struggle during high-demand periods, hampering the experience of residents and visitors alike.

6. Results and Discussion

6.1 Reduction in traffic congestion

Although Almadinah Almunawarah has expanded its public transportation network, the current systems remain insufficient to handle the city's influx of visitors during peak seasons. Public transportation primarily consists of bus services, taxis, and limited ride-sharing options. Figure 2 shows the existing Bus Rapid Transit (BRT) network, while Figure 3 presents a conceptual map of the public BRT system. Some roads are still undergoing modifications to accommodate the BRT system. By 2030, the infrastructure aims to include 300 to 500 stations, 80 to 100 buses, 30 to 40 million annual trips, a 400 to 800-meter service buffer, and 80 to 90% area coverage.

The current BRT system can be easily upgraded to incorporate an Autonomous-Rail Rapid Transit (ART) system, offering several advantages. ART can accommodate up to 300 passengers per trip, significantly surpassing the 50-passenger capacity of BRT buses. The large influx of pilgrims during Hajj and Umrah exerts heavy pressure on the city's roads and

transportation systems. By providing a high-capacity, efficient alternative, ART reduces traffic congestion during these peak periods. Unlike buses and private vehicles, ART minimizes the number of vehicles on the road by transporting more passengers per trip, easing bottlenecks and improving the flow of traffic in critical areas.

Figure 14. Conceptual map of the current public transport network in Almadinah Almunawarah.

Figure 15. Public Transport Network for Almadinah Almunawarah.

6.2 Flexibility and scalability of ART

ART's flexibility and scalability make it well-suited to handle fluctuating passenger demands. During peak periods, such as major religious events, the system can increase service frequency or deploy additional vehicles to manage surges in ridership. In contrast, during off-peak times, ART can reduce operations to match lower demand, optimizing energy consumption and cutting operational costs. This adaptability ensures year-round efficiency, making ART a practical and cost-effective solution for Almadinah Almunawarah's unique transit needs. If the existing BRT system is upgraded to ART, the new system can share routes with other transportation modes, as shown in Figure 3, while maintaining greater operational flexibility and scalability.

Moreover, ART is well-suited for future urban growth and fluctuations in visitor numbers. Almadinah Almunawarah continues to grow as a major religious destination and urban center, meaning that transportation needs will expand over time. ART's infrastructure-light design makes it easier to expand or modify routes as the city's population and visitor numbers increase. The system's ability to adapt to changing conditions without requiring significant overhauls or infrastructure investments positions ART as a sustainable solution for the city's long-term development. It provides a

flexible framework that can evolve with Almadinah Almunawarah's transportation needs, ensuring seamless integration with ongoing urban expansion.

6.3 Smart Mobility Solutions

The use of Autonomous-Rail Rapid Transit (ART) systems goes beyond efficient transportation; it plays a pivotal role in optimizing crowd control through the integration of advanced smart technologies. ART systems rely heavily on artificial intelligence (AI) and big data analytics to manage large crowds effectively. By leveraging AI, ART can analyze patterns in passenger movement, predict congestion points, and adjust its operations dynamically to avoid bottlenecks. These capabilities allow for smoother, more controlled crowd flow, especially during peak periods such as Hajj and Umrah when Almadinah Almunawarah experiences a massive influx of visitors. Smart algorithms continuously process real-time data, enabling ART to make precise, data-driven decisions that enhance the overall transit experience while minimizing delays and overcrowding.

In addition, real-time data analysis plays a crucial role in improving operational efficiency and ensuring crowd safety. ART systems collect and process data from multiple sources, including sensors, passenger apps, and traffic monitoring systems. This real-time information allows the system to adjust its frequency, route schedules, and vehicle capacities in response to fluctuating demand, reducing the risk of overcrowding at stations or on the vehicles themselves. For example, if an ART station begins to experience a surge in passengers, the system can immediately deploy additional vehicles or reroute services to alleviate pressure. This not only keeps operations running smoothly but also ensures passenger safety by preventing hazardous crowd densities.

Furthermore, the continuous monitoring of crowd movement and system performance provides valuable insights into how the system can be optimized over time. Through predictive analytics, ART systems can anticipate high-demand periods, such as festival seasons or unexpected events, and prepare accordingly. These smart mobility solutions enable ART to remain adaptive, offering a flexible response to crowd dynamics while maintaining safety and operational integrity. This real-time adaptability makes ART a highly efficient tool for managing large crowds and optimizing urban mobility in an ever-growing city like Almadinah Almunawarah.

7. Conclusion

This study sets out to explore how implementing an Autonomous-Rail Rapid Transit (ART) system can address the growing challenges of urban mobility and crowd management in Almadinah Almunawarah. With the city experiencing an influx of millions of visitors during peak events like Hajj and Umrah, existing transportation systems struggle to meet demand, leading to congestion, delays, and environmental issues. Through proposing ART as a scalable, sustainable transit solution, the research aimed to determine how this technology could enhance transportation efficiency, support crowd control, and align with the city's long-term urban development and sustainability goals.

The findings highlight several key advantages of ART for urban mobility in Almadinah Almunawarah. ART's capacity to accommodate up to 300 passengers per trip offers a significant improvement over existing Bus Rapid Transit (BRT) systems, easing congestion by reducing the number of vehicles on the road. The flexibility of ART allows it to adapt to fluctuating demand, with the ability to increase frequency during peak periods and scale back operations during off-peak times, optimizing costs and energy use. Moreover, the system's ability to operate on virtual tracks without requiring extensive infrastructure investments makes it a cost-effective and adaptable solution. Additionally, the integration of smart technologies, such as artificial intelligence and real-time data analytics, allows ART to manage crowds efficiently

and ensure smooth operations, particularly during high-demand periods like Hajj and Umrah. Global case studies demonstrate ART's success in cities such as Zhuzhou and Yibin, offering valuable insights into its potential application in Almadinah Almunawarah.

While the study provides valuable insights, certain limitations should be acknowledged. The analysis relies primarily on case studies from other cities, which may differ in infrastructure, culture, and transportation needs from Almadinah Almunawarah. As a result, the direct applicability of those solutions may be constrained by the city's unique characteristics. Additionally, the study focuses on the potential benefits of ART without extensively evaluating the financial, regulatory, and technical challenges that may arise during implementation. These limitations suggest the need for further investigation before large-scale deployment.

Building on the findings and addressing the identified limitations, future research should explore several areas. First, pilot programs or simulation studies in Almadinah Almunawarah could provide empirical data on ART's performance in the local context, helping refine strategies for full-scale implementation. Additionally, future research could examine the financial and regulatory frameworks necessary to support ART deployment, including investment strategies and policy alignment. Finally, investigating passenger experiences and public acceptance of ART will be essential to ensure community support and long-term success. These efforts will contribute to a deeper understanding of how ART can serve as a transformative force in urban mobility and crowd management in Almadinah Almunawarah.

8. Recommendations

To ensure the successful adoption and seamless integration of ART in Almadinah Almunawarah, a phased deployment strategy is essential. Initial implementation should focus on high-demand corridors, such as routes serving the Prophet's Mosque and Airport, to alleviate congestion during peak periods. Investment strategies should prioritize both public and private funding, with incentives to attract technology providers and operators. Additionally, integrating ART with existing Bus Rapid Transit (BRT) systems will enhance flexibility, allowing shared routes and smooth transition phases. To optimize operations, the city should leverage smart technologies, such as artificial intelligence and real-time data analytics, for adaptive scheduling and efficient crowd control.

References

[1]M. A. R. Abdeen, A. Beg, S. M. Mostafa, A. AbdulGhaffar, T. R. Sheltami, and A. Yasar, "Performance Evaluation of VANET Routing Protocols in Madinah City," Electronics (Basel), vol. 11, no. 5, p. 777, Mar. 2022, doi: 10.3390/electronics11050777.

[2]M. A. R. Abdeen, I. A. Nemer, and T. R. Sheltami, "A Balanced Algorithm for In-City Parking Allocation: A Case Study of Al Madinah City," Sensors 2021, Vol. 21, Page 3148, vol. 21, no. 9, p. 3148, May 2021, doi: 10.3390/S21093148.

[3]T. ; Li et al., "A Convolutional Fuzzy Neural Network Active Noise Cancellation Approach without Error Sensors for Autonomous Rail Rapid Transit," Processes 2023, Vol. 11, Page 2576, vol. 11, no. 9, p. 2576, Aug. 2023, doi: 10.3390/PR11092576.

[4]F. Jianghua, H. Yunqing, Y. Xiwen, H. Ruipeng, X. Lei, and Z. Chenlin, "Autonomous-rail Rapid Transit Tram: System Architecture, Design and Applications," Green Energy and Intelligent Transportation, p. 100161, Jan. 2024, doi: 10.1016/J.GEITS.2024.100161.

[5]S. Sunardi et al., "Autonomous Rail Rapid Transit (ART) Prototype Concept Using Wireless Charging System with Electromagnetic Induction Coupling," Journal of Railway Transportation and Technology, vol. 1, no. 1, pp. 1–12, May 2022, doi: 10.37367/jrtt.v1i1.4.

[6]S. Fang, J. Ma, and Y. Wang, "Research on Comparison of Tram with BRT," 2018, pp. 165–174. doi: 10.1007/978-981-10-3551-7_12.
[7]Z. Wang, Z. Lu, J. Wei, and X. Qiu, "Research on Virtual Track Train Path-Tracking Control Based on Improved MPC and Hierarchical Framework: A Reconfigurable Approach," Applied Sciences, vol. 13, no. 14, p. 8443, Jul. 2023, doi: 10.3390/app13148443.
[8]A. Mushtaq, I. U. Haq, M. U. Imtiaz, A. Khan, and O. Shafiq, "Traffic Flow Management of Autonomous Vehicles Using Deep Reinforcement Learning and Smart Rerouting," IEEE Access, vol. 9, pp. 51005–51019, 2021, doi: 10.1109/ACCESS.2021.3063463.
[9]D. Han, J. Wang, Y. Yan, M. Wu, Z. Lin, and Y. Guodong, "Velocity Planning of the Autonomous Rail Rapid Transit with Consideration of Obstacles," in 2020 4th CAA International Conference on Vehicular Control and Intelligence (CVCI), IEEE, Dec. 2020, pp. 35–40. doi: 10.1109/CVCI51460.2020.9338562.
[10]T. Li, S. Zhang, G. Xiao, M. Wang, H. Zhong, and J. Feng, "Brake Instability Dynamic Model and Active Control Strategy for a Multiunit Articulated Rubber-Wheel Autonomous Rail Rapid Transit System," Sustainability, vol. 14, no. 21, p. 14531, Nov. 2022, doi: 10.3390/su142114531.
[11]D. Han, J. Wang, Y. Yan, M. Wu, Z. Lin, and Y. Guodong, "Velocity planning of the autonomous rail rapid transit with consideration of obstacles," 2020 4th CAA International Conference on Vehicular Control and Intelligence, CVCI 2020, pp. 35–40, Dec. 2020, doi: 10.1109/CVCI51460.2020.9338562.
[12]Q. Zhang, F. Yan, W. Song, R. Wang, and G. Li, "Automatic Obstacle Detection Method for the Train Based on Deep Learning," Sustainability, vol. 15, no. 2, p. 1184, Jan. 2023, doi: 10.3390/su15021184.
[13]S. Liu, C. Li, T. Yuwen, Z. Wan, and Y. Luo, "A Lightweight LiDAR-Camera Sensing Method of Obstacles Detection and Classification for Autonomous Rail Rapid Transit," IEEE Transactions on Intelligent Transportation Systems, vol. 23, no. 12, pp. 23043–23058, Dec. 2022, doi: 10.1109/TITS.2022.3194553.
[14]X. Duan, H. Jiang, D. Tian, T. Zou, J. Zhou, and Y. Cao, "V2I based environment perception for autonomous vehicles at intersections," China Communications, vol. 18, no. 7, pp. 1–12, Jul. 2021, doi: 10.23919/JCC.2021.07.001.
[15]V. H. Prasad Reddy, A. Ravi Raja, P. K. Polasi, R. T. Ponnuri, G. K. Kumar, and S. F. Ahamed, "Design and Development of Traffic Light Recognition method for Autonomous vehicles using V2I Communication," in 2023 3rd International conference on Artificial Intelligence and Signal Processing (AISP), IEEE, Mar. 2023, pp. 1–6. doi: 10.1109/AISP57993.2023.10134974.

Implementing an AI-driven ED System for Efficient Emergency Management during Hajj

Hassan Hijry*[1], Fares S. Almehmadi[2]

[1]*Department of Indusrtial Engineering, University of Tabuk

[2]Department of Electrical Engineering, University of Tabuk

*Corresponding author: E-mail (hhegri@ut.edu.sa)

تطوير نظام ذكي يعتمد على الذكاء الاصطناعي لتحسين وإدارة قسم الطوارئ بكفاءة خلال موسم الحج

حسن هجري*[1]، فارس صالح المحمادي[2]

قسم الهندسة الصناعية، جامعة تبوك*[1]

قسم الهندسة الكهربائية، جامعة تبوك[2]

Abstract

The transformation of emergency departments (EDs) into smart systems is pivotal for enhancing modern healthcare, especially in managing patient overcrowding. Over 50% of hospital admissions stem from EDs, and this challenge is exacerbated during large-scale events such as the Hajj pilgrimage in Mecca, Saudi Arabia. Managing the surge in patient demand during such events is critical to ensuring smooth patient flow and maintaining operational efficiency. In response to this challenge, this paper introduces an Intelligent ED system that integrates AI technologies, including machine learning and data analytics, to predict and manage hospital congestion during Hajj. The system leverages electronic health record (EHR) data (e.g., arrival, exam, and discharge times) to forecast patient waiting times using deep neural networks. By analyzing real-time ED workflows—such as triage and diagnostics—our AI model aims to optimize patient flow and prevent bottlenecks. Among the models tested, (Long Short-Term Memory (LSTM), Deep Neural Network (DNN), and Bidirectional LSTM (BiLSTM), the traditional LSTM network demonstrated exceptional performance, achieving a minimal Mean Absolute Error (MAE) of 2.09 and an R^2 of 0.98.

Its ability to effectively capture sequential dependencies, such as afternoon surges in crowd patterns, highlights its suitability for forecasting patient flow during peak demand periods. The system is user-friendly, deployed via Streamlit for non-technical users, and adaptable to queue systems in healthcare settings. Expected outcomes include improved ED efficiency, reduced patient waiting times, and better resource allocation during peak periods. These AI-driven insights will empower decision-makers and healthcare authorities to enhance emergency management not only in Mecca and Medina, but also in EDs worldwide, particularly during mass gatherings or large-scale events.

Keywords: Intelligent ED system, smart healthcare, patient flow optimization, crowding management, LSTM, DDN.

1. Introduction

The healthcare system relies heavily on accurate cost and resource allocation, especially considering patient length of stay. Projections help model bed capacity and staffing needs over time. Common forecasting methods include 12-month moving averages, trend lines, and seasonalized forecasts, which incorporate historical data to adjust for trends and seasonal variations [1]. Modeling patient flow using compartmental, queuing, and simulation methods enables better tactical and strategic planning [2], [3]. For example, a study conducted by [4], was introduced to improve patient workflow processes in the emergency department (ED) of a smart city. The study used Machine Learning Control (MLC), the Internet of Things (IoT), and Discrete Event Simulation (DES) to optimize patient flow. Key metrics, such as bed occupancy, patient arrivals, and length of stay, provide insights into long-term patient flow [5], [6], [7]. Emergency and acute care departments particularly focus on these metrics for quality of care assessments [8], [9]. Machine learning has emerged as a powerful tool for predictive modeling, addressing challenges like patient flow forecasting [10]. Moreover, Electronic Health Records (EHR) streamline data management, ensuring better planning, diagnosis, and prognosis through digital records [11]. These records integrate structured and unstructured data, enabling efficient exchange and analysis across healthcare settings [12]. Machine learning in healthcare further enhances outcomes by predicting chronic diseases, reducing readmission rates, and improving financial performance through personalized interventions and predictions [13]. As healthcare continues evolving, advanced forecasting methods and technology integration are key drivers for improvement. A well-designed hospital management system also incorporates predictive analytics to manage staffing and reduce costs associated with under or overstaffing [10]. Predictive staffing tools leverage patient admission and discharge patterns, contributing to more efficient and responsive hospital operations. Such systems also optimize the patient-to-staff ratio, allowing healthcare institutions to meet demand without sacrificing care quality [14]. Effective data integration, especially in larger healthcare facilities, is crucial for managing and synthesizing diverse data sources, such as imaging systems, patient monitoring devices,

EHRs, and wearable technology [15]. These sources often generate massive amounts of data that need to be processed in real time to support timely interventions and personalized care. Advanced data integration platforms not only ensure seamless communication between these systems but also enable healthcare providers to access a unified view of patient information, leading to better care coordination and reduced redundancies. Furthermore, these platforms improve operational efficiency by automating workflows and reducing manual data entry, minimizing the risk of errors. Interoperable systems play a pivotal role in enabling real-time data sharing across departments, ensuring that all healthcare professionals involved in patient care are on the same page. This integration supports faster clinical decision-making, enhances patient safety, and improves the overall quality of care by streamlining complex processes across departments and ensuring continuity of care.

The growing role of artificial intelligence (AI) in healthcare decision-making has also revolutionized diagnostics and patient care management [17]. AI-based algorithms, applied to medical imaging, electronic records, and genetic data, enable early detection of diseases, improved treatment planning, and personalized healthcare solutions. Integrating AI-driven insights into clinical workflows helps reduce diagnostic errors, shortens time to diagnosis, and enhances therapeutic outcomes. This, in turn, supports the overall aim of improving healthcare delivery, reducing costs, and promoting patient-centric care [18].

This research presents an intelligent emergency department (ED) system that leverages deep learning models to predict patient flow and manage overcrowding during high-demand periods, like the Hajj pilgrimage. It explores different AI models, with the Long Short-Term Memory (LSTM) network standing out for its ability to recognize patterns over time, including daily surges in patient arrivals. By integrating AI into ED operations, the system aims to optimize resource allocation, reduce bottlenecks, and improve patient care, ensuring smooth and efficient operations during peak events.

2. Methodology

In this study, we developed and deployed a machine learning model to predict emergency room (ER) wait times and assist in hospital location services. The model processes data such as patient arrival rates, and triage severity levels. Data cleaning and standardization have been done using outlier detection and min-max standardization. The model prediction has been implemented with LSTM, Deep Neural Network (DNN), and Bidirectional (BiLSTM). The traditional LSTM has been selected to predict waiting time. For model training and testing, we used data extracted from the Triage Monitoring system [19], which included the time of checking into the queue (arrival/registration time), time spent in the queue (waiting time), time spent at the server point (service time/exam by doctor), and the total time spent in the entire system (length of stay).

While real-time IoT sensor inputs were proposed for future integration to enhance the model's predictions. The system was deployed in a cloud-based environment, providing real-time predictions accessible to healthcare providers, patients, and ambulances via a user-friendly platform, as shown in Figure 1. The platform includes a map-based hospital locator and a wait-time predictor, offering accurate, dynamic estimates that help optimize patient flow and resource allocation during emergencies. Continuous updates from new data ensure the model's long-term accuracy, with real-world validation conducted during high-demand scenarios such as Hajj season.

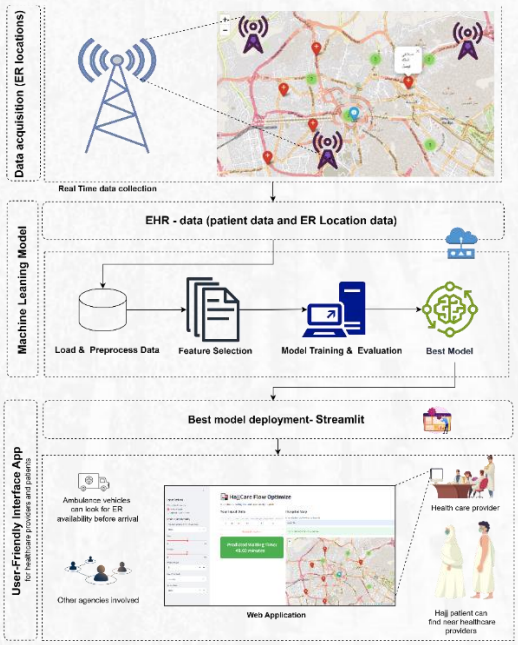


Figure 16. The proposed methodology.

2.1. LSTM

LSTM networks were selected due to their ability to capture long-term dependencies in sequential data, which is crucial for waiting time prediction. The architecture consists of three main gates—input, forget, and output—which control the flow of information through time steps. The model's equations (illustrated in Figure 2) govern how information is retained or discarded, ultimately updating the cell state C_t and hidden state h_t. These operations are essential for maintaining relevant past information and discarding less important data. This allows the model to understand long-term temporal relationships in the time series data, as depicted in Figure 2, [20][21].

Forget gate: $f_t = \sigma(W_f \cdot [h_{\{t-1\}}, x_t] + b_f)$
Input Gate: $i_t = \sigma(W_i \cdot [h_{\{t-1\}}, x_t] + b_i)\{C\}_t = tanh(W_C \cdot [h_{\{t-1\}}, x_t] + b_C)$
Cell State Update: $C_t = f_t * C_{\{t-1\}} + i_t * \{C\}_t$
Output Gate: $o_t = \sigma(W_o \cdot [h_{\{t-1\}}, x_t] + b_o)h_t = o_t * tanh(C_t)$
Where
$ft, iti_{tit}, and\ oto_{tot}$ are the forget, input, and output gates, respectively
$Wf, WiW_{iWi}, WoW_{oWo}, and\ WCW_{CWC}$ are weight matrices.
$Ct\ is\ the\ cell\ state\ at\ time\ t, and\ h_t is\ the\ hidden\ state\ at\ time\ t$.

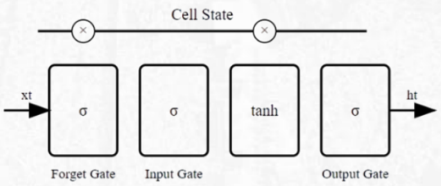


Figure 2. Traditional long short-term memory model structure.

2.2. BiLSTM

The BiLSTM enhances the traditional LSTM by adding a second layer that processes the sequence in reverse. This enables the model to learn dependencies from both past and future time steps simultaneously. Figure 3 shows the architecture, where forward and backwards hidden states $h_t^{forward}$ and $h_t^{backward}$ are concatenated at each time step to form the final output. This configuration allows the BiLSTM to capture more intricate relationships within the dataset, though the results (explored later) indicate that this added complexity may have led to overfitting [22].

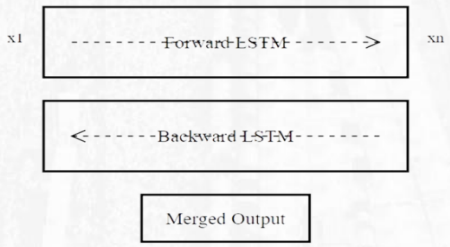


Figure 3. Bidirectional long short-term memory structure.

The output of a BiLSTM is the concatenation of the forward and backwards hidden states:

$$h_t = Concat(h_t^{forward}, h_t^{backward})$$

Where $h_t^{forward}$ represents the hidden state from the forward LSTM, and $h_t^{backward}$ is from the backward LSTM.

2.3. Deep Neural Network (DNN)

A (DNN) is a feed-forward neural network with multiple layers (usually called "hidden layers") between the input and output layers. DNNs aim to capture complex patterns in data by learning hierarchical representations. Each layer in a DNN applies a non-linear transformation to its input, usually through an activation function like ReLU, [23][24].

Mathematically, the forward propagation through a layer is defined as:

$$a(1) = \sigma(\mathrm{W(l)a(l-1) + b(l)})\mathrm{a^{\{(l)\}}} = \sigma\left(\mathrm{W^{\{(l)\}a^{\{(l-1)\}}} + b^{\{(l)\}}}\right)\mathrm{a(l)} = \sigma(\mathrm{W(l)a(l-1) + b(l)})$$

Where:

- $\mathrm{a(l)a^{\{(l)\}a(l)}}$ is the activation of the lll-th layer,
- $\mathrm{W(l)W^{\{(l)\}W(l)}}$ is the weight matrix of the lll-th layer,
- $\mathrm{b(l)b^{\{(l)\}b(l)}}$ is the bias term,
- $\sigma\backslash\mathrm{sigma}\sigma$ is of the activation function (e.g., ReLU or sigmoid).

In DNNs, the goal is to minimise the loss function (e.g., mean squared error for regression tasks) through backpropagation, which updates the weights and biases across all layers.

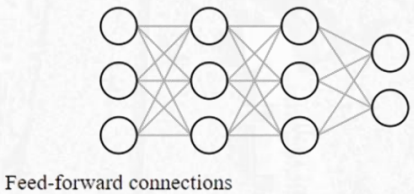


Figure 3. Deep neural network architecture.

2.4. Streamlit Web Application

The developed application offers several key features designed to enhance usability and functionality for healthcare providers and patients as shown in Figure 1. *Data upload* allows users to upload datasets in CSV or XLSX formats, with the ability to select target and feature columns interactively. The platform facilitates data preprocessing for training and scaling to prepare the dataset for model development. In *Model Training*, users can choose from three model types: Traditional LSTM, Advanced LSTM, and DNN. The model is trained on the uploaded dataset, and performance metrics such as Mean Absolute Error (MAE), Mean Squared Error (MSE), and R-squared (R^2) are displayed for evaluation.

The *evaluation & visualization* module enables users to visualize actual vs. predicted values, residual plots, and comprehensive performance metrics, with interactive features for error analysis and other model performance visualizations. The application also includes an *Interactive Map*, where users can enter a city name and locate nearby hospitals using data from OpenStreetMap. The search radius can be customized in meters to display hospitals within a preferred distance. These features collectively improve decision-making by offering real-time data and user-friendly tools for hospital location and patient flow management.

3. Results and Discussion

Each model was evaluated using MAE, Mean Squared Error (MSE), and R^2 as key performance indicators (see Table below).

Table 1. The model comparison and results.

Model	MSE	MAE	R^2
Traditional LSTM	**6.98**	**2.09**	**0.98**
Advanced LSTM	16.13	2.33	0.96
DNN	427.82	17.59	0.02

3.1. LSTM Performance:

The traditional LSTM outperformed, achieving near-perfect performance with a minimal MAE of 2.09 and an R^2 of 0.98. Figure 4 shows shows model performance on the predicted values against to actual dataset, the straight refers to the best fit line for the data distribution while the scatter dots represent the data distribution, it can be seen that some data point very close and even perfectly intersect with the best fit line, while the some of them has a distance between the best fit line and data point, the distance shows that model prediction error. Its ability to learn and predict cyclic crowd patterns, especially during afternoon surges, highlights its effectiveness in capturing sequential dependencies. The learning curve in Figure 5 shows that both training and validation losses converged within the first 8 epochs, indicating rapid learning without overfitting. The relatively stable performance across subsequent epochs supports the robustness of the LSTM in time-series prediction tasks.

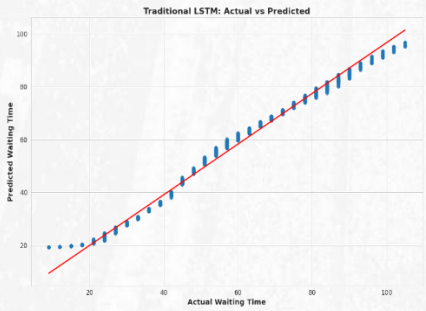


Figure 4. Traditional LSTM prediction and actual plot with data distribution on the best fit line.

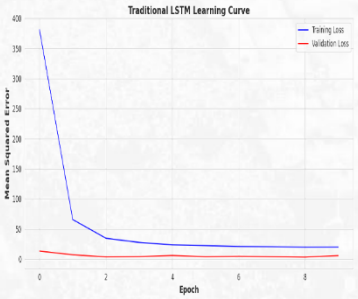


Figure 5. Traditional LSTM learning curve.

3.1. BiLSTM Performance

Figure 6 demonstrates the model's performance by comparing predicted values to the actual dataset. The straight line represents the best-fit line for the data distribution, while the scatter points indicate the actual data distribution. It can be observed that some data points closely align with, or even perfectly intersect, the best-fit line, whereas others deviate, reflecting the model's prediction error. While the BiLSTM model exhibited strong performance, achieving an R^2 of 0.96, it showed slightly higher prediction errors with a MAE of 2.33 and a Mean Squared Error (MSE) of 0.55 compared to the traditional LSTM.

This marginal increase in error, visualized in Figure 6, could be due to the added complexity of processing data bidirectionally, which might have made the model more sensitive to noise or fluctuations in less volatile periods. The error distribution in Figure 7 demonstrates that while the BiLSTM handled most predictions accurately, it exhibited greater variance in error compared to the LSTM.

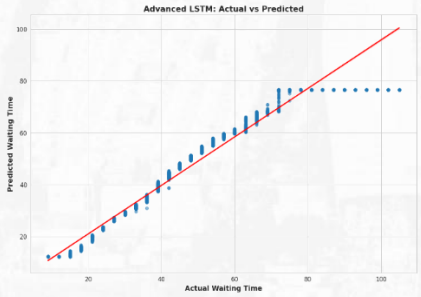


Figure 6. BiLSTM prediction and actual plot with data distribution on the best fit.

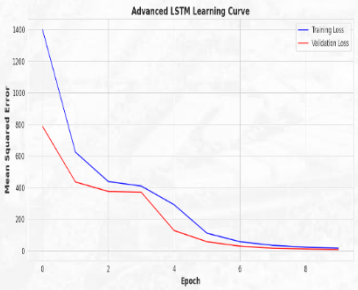


Figure 7. BiLSTM learning curve.

3.3. DNN Performance

Figure 8 illustrates the model's performance by comparing predicted values vs actual dataest. The straight line represents the best fit line for the data, whole the scatter dots reflect the actual data distribution. As shown, some data points closely align with and some other deviate which indicating prediction errors. The DNN struggled to match the performance of the LSTM and BiLSTM models, achieving a significantly higher MAE (17.59) and MSE (427.82) with an R^2 of 0.02.

This outcome, shown in Figure 9, highlights the DNN's difficulty in handling sequential data, which is critical for accurately predicting waiting times. The model failed to capture the temporal dependencies present in the data, leading to overpredictions and underpredictions, particularly during peak service hours.

The increase in error could be attributed to overfitting or a higher sensitivity to noise within the data, despite its improved capacity to model intricate relationships. In contrast, the DNN, which lacks the sequence-processing capabilities inherent in LSTM architectures, struggled to Although the model captured some general trends, it was less capable of modeling the temporal relationships required for accurate waiting time predictions.

This performance discrepancy between LSTM models and the DNN underscores the importance of leveraging time-series-specific architectures when dealing with sequential data. The results also suggest that while the advanced LSTM introduces additional complexity, the traditional LSTM remains more robust and generalizable across various periods.

The learning curve for the traditional LSTM model demonstrates rapid convergence, with both training and validation losses decreasing significantly within the first a few epochs. This indicates that the model quickly learns the underlying temporal patterns in the data.

The close alignment between training and validation losses suggests strong generalization, with no signs of overfitting. After the initial convergence, both losses stabilize, with minimal improvements observed in subsequent epochs. This result highlights the efficiency of the LSTM model in time-series prediction tasks and suggests that early stopping could be employed to optimize training time.

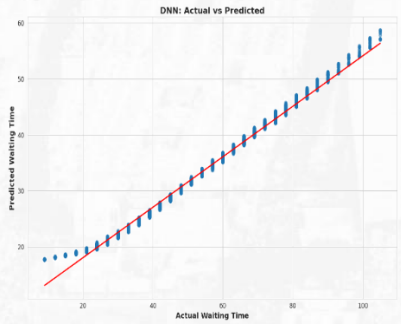


Figure 8. DNN prediction and actual plot with data distribution on the best fit line.

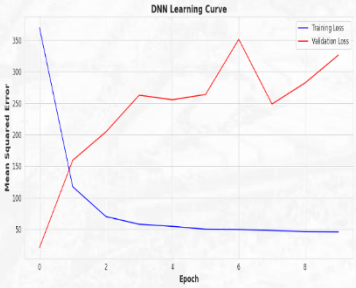


Figure 9. DNN learning curve.

3.4. AI Models Prediction Error Distribution

The prediction error distribution for each model offers deeper insights into their respective strengths and weaknesses. As shown in Figure 10, the traditional LSTM model maintained a concentrated error distribution, with most errors lying between -2.5 and 10.0, indicating consistently accurate predictions. Conversely, the BiLSTM (Figure 11) displayed a broader error range from -5.0 to 5.0, pointing to greater variability and a slightly reduced ability to generalize during periods of lower crowd activity.

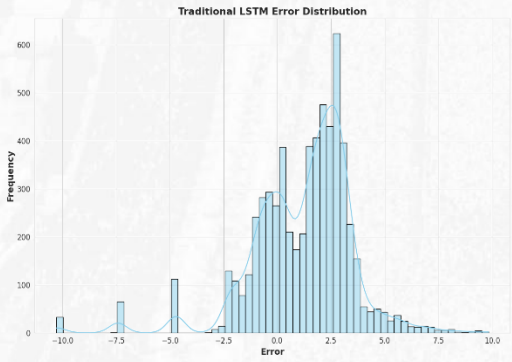


Figure 10. Traditional LSTM prediction error histogram.

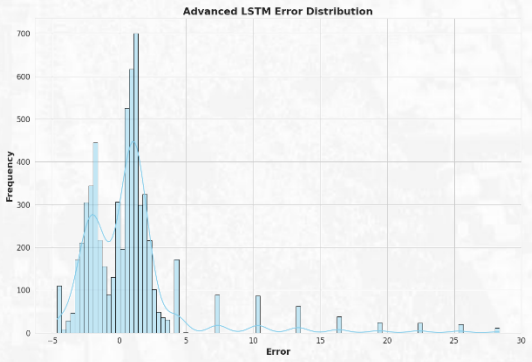


Figure 11. BiLSTM prediction error histogram.

The DNN's error distribution (Figure 12) reveals significant variance, with errors spanning from -10 to +2 and peaks around -8 and 2. This wide spread of errors underscores the DNN's inability to model the sequential nature of the data. As a result, it consistently generated inaccurate predictions, especially during critical high-traffic periods.

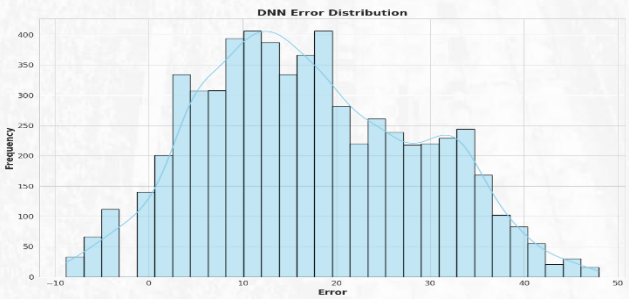


Figure 12. DNN prediction error histogram.

3.1. Discussion

The evaluation of LSTM networks for time-series forecasting in service-related waiting times has revealed several key insights, supported by the predictive patterns observed. The results emphasize the LSTM's capacity to effectively model sequential data, capturing both short- and long-term temporal dependencies. Notably, the traditional LSTM model demonstrated exceptional performance, achieving near-perfect accuracy across multiple evaluation metrics. This superiority can be attributed to its ability to track and adapt to fluctuations in waiting times throughout the day, as seen in the predictions for both crowd patterns and service time. Figure 13, depicting predicted crowd patterns for the next 24 hours, highlights several critical time intervals (15:00, 19:00, and 22:00) marked by potential crowd surges. These peak times align with real-world service congestion trends, particularly in sectors where user footfall increases during the afternoon and early evening. The ability of the traditional LSTM to forecast these peaks accurately demonstrates its effectiveness in handling sequential dependencies inherent in time-series data, as crowd behavior typically follows repeatable, cyclical patterns across days.

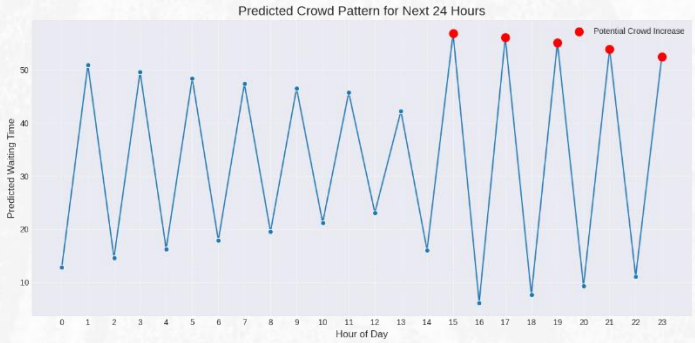


Figure 13. Crowd patterns for the next 24 hours.

In contrast, while the bidirectional LSTM introduced more complexity into the architecture by processing data from both forward and backward sequences, this model slightly underperformed in comparison to the traditional LSTM. The increase in prediction error suggests the bidirectional model may have been overly sensitive to minor fluctuations, leading to potential overfitting. This is particularly evident during less volatile periods, where the simpler dependencies captured by the traditional LSTM were sufficient for accurate prediction.

The limited complexity of the dataset, which primarily consists of periodic peaks and valleys, may explain why the bidirectional LSTM failed to capitalize on its inherent advantages, such as modeling bidirectional time dependencies. Figure 14, illustrating predicted service times, provides further evidence of the LSTM's predictive capability, particularly in identifying critical periods where service times are expected to exceed the 75th percentile threshold. Between 12:00 and 16:00, predicted service times exceed 55 minutes, with several spikes marked as potential crowd times. This trend suggests an alignment between periods of high crowd concentration and extended service times, a valuable insight for managing operational capacity during peak periods.

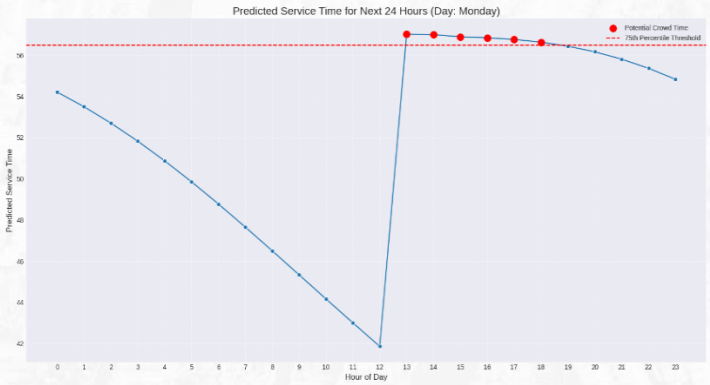


Figure 14. Predicted service times.

The DNN struggled with time-series forecasting due to its inability to capture the sequential nature of the data, leading to significant prediction errors during peak service times. This highlights the importance of choosing appropriate models for time-series problems. An application was developed using a more effective model to predict patient wait times, featuring a user-friendly interface accessible to both healthcare providers and patients. It offers a map-based hospital locator, real-time wait-time predictions, and integration with services like ambulance systems, as shown in Figure 15 (screenshot). The platform supports data visualization and ensures accuracy through continuous updates, with real-world validation conducted during high-demand events, such as the Hajj season.

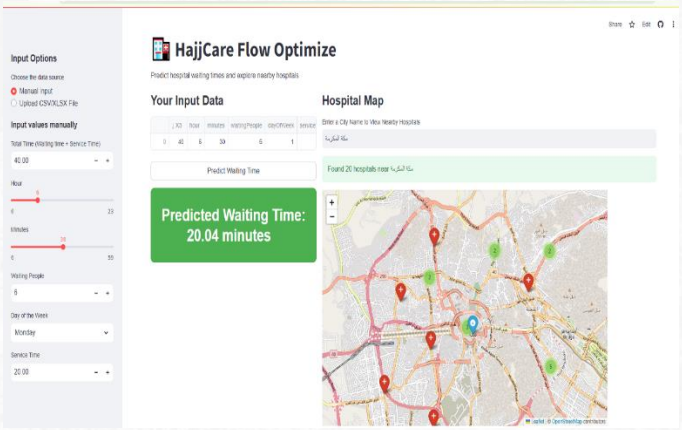


Figure 15. Model deployment.

4. Conclusion

Accurate cost and resources allocation is critical for the healthcare systems. Forecasting enables effective modeling of resources and staffing requirements over time. This study highlights the strengths and limitations of different machine learning models for predicting service-related waiting times. LSTM networks, particularly the standard LSTM, proved to be highly effective for time-series forecasting due to their ability to capture temporal dependencies within the data. Although the BiLSTM added complexity, it did not significantly improve performance, indicating that simpler models can sometimes be more suitable when dealing with straightforward temporal patterns. In contrast, the DNN struggled with sequential data, limiting its predictive accuracy for waiting times. The comparative analysis showed that traditional LSTM is the most effective model for time-series forecasting, with an MSE of 6.98, MAE of 2.09, and R^2 of 0.98. The results

emphasize the importance of selecting the right model for time-series data to accurately capture patterns and dependencies. A key finding was the model's ability to identify peak crowding times, such as afternoon surges, which offers valuable insights for better resource planning and management. In future work, the model will be implemented in the local hospital's ER system and integrated with the electronic health records system to enable real-time predictions and support more effective decision-making. This integration will improve overall ED efficiency, reduce patient waiting times, and optimize resource allocation during peak periods, ultimately alleviating crowding and enhancing the performance of the entire healthcare system.

References

1. E. Kulinskaya, D. Kornbrot, and H. Gao, "Length of stay as a performance indicator: Robust statistical methodology," IMA J. Manag. Math., vol. 16, no. 4, p. Pages. 369–381, 2005, doi: 10.1093/imaman/dpi015.
2. I. Batal, H. Valizadegan, G. F. Cooper, and M. Hauskrecht, "A temporal pattern mining approach for classifying electronic health record data," ACM Trans. Intell. Syst. Technol., vol. 4, no. 4, 2013, doi: 10.1145/2508037.2508044
3. S. J. Nelson, K. Zeng, J. Kilbourne, T. Powell, and R. Moore, "Normalized names for clinical drugs: RxNorm at 6 years," J. Am. Med. Informatics Assoc., vol. 18, no. 4, pp. 441–448, Jul. 2011, doi: 10.1136/amiajnl-2011-000116.
4. Hijry, H. (2024, June). Proposed Model for NEOM City Based on Internet of Things (IoT) and MLC at ED System. In 2024 IEEE International Conference on Prognostics and Health Management (ICPHM) (pp. 23-32). IEE
5. D. E. Clark and L. M. Ryan, "Concurrent Prediction of Hospital Mortality and Length of Stay from Risk Factors on Admission," Health Serv. Res., vol. 37, no. 3, pp. 631–645, Jun. 2002, doi: 10.1111/1475-6773.00041.
6. Chandan K. Reddy and Rajiur Rahman., Electronic Health Records: A Survey in Healthcare Data Analytics. 2014.
7. R. Schmidt and L. Gierl, "A prognostic model for temporal courses that combines temporal abstraction and case-based reasoning," Int. J. Med. Inform., vol. 74, no. 2–4, pp. 307–315, Mar. 2005, doi: 10.1016/j.ijmedinf.2004.03.007.
8. L. Sacchi, C. Larizza, C. Combi, and R. Bellazzi, "Data mining with Temporal Abstractions: Learning rules from time series," Data Min. Knowl. Discov., vol. 15, no. 2, pp. 217–247, Oct. 2007, doi: 10.1007/s10618-007-0077-7.
9. C. C. Bennett, "Utilizing RxNorm to support practical computing applications: Capturing medication history in live electronic health records," J. Biomed. Inform., vol. 45, no. 4, pp. 634–641, 2012, doi: 10.1016/j.jbi.2012.02.011.
10. A. Esteva et al., "Dermatologist-level classification of skin cancer with deep neural networks," Nature, vol. 542, no. 7639, pp. 115–118, Feb. 2017, doi: 10.1038/nature21056.
11. Y. Shahar and M. A. Musen, "Knowledge-based temporal abstraction in clinical domains," Artif. Intell. Med., vol. 8, no. 3, pp. 267–298, 1996, doi: 10.1016/0933-3657(95)00036-4.
12. F. Wang, N. Lee, J. Hu, J. Sun, and S. Ebadollahi, Towards Heterogeneous Temporal Clinical Event Pattern Discovery:A Convolutional Approach. 2012.
13. R. Miotto, L. Li, B. A. Kidd, and J. T. Dudley, "Deep Patient: An Unsupervised Representation to Predict the Future of Patients from the Electronic Health Records," Sci. Rep., vol. 6, May 2016, doi: 10.1038/srep26094.
14. R. Cornet and N. de Keizer, "Forty years of SNOMED: a literature review," BMC Med. Inform. Decis. Mak., vol. 8, no. S1, p. S2, Oct. 2008, doi: 10.1186/1472-6947-8-S1-S2.
15. W. H. O. (WHO). World Health Organization (WHO). and Information Systems, "WHO | ICD-11 Timeline," 2019. https://www.who.int/classifications/icd/revision/timeline/en/ (accessed Nov. 11, 2019).
16. T. Pham, T. Tran, D. Phung, and S. Venkatesh, "DeepCare: A deep dynamic memory model for predictive medicine," in Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), 2016, vol. 9652 LNAI, pp. 30–41, doi: 10.1007/978-3-319-31750-2_3

17. T. D. Nguyen, T. Tran, D. Phung, and S. Venkatesh, "Latent patient profile modelling and applications with mixed-variate restricted Boltzmann machine," in Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), vol. 7818 LNAI, no. PART 1, 2013, pp. 123—135

18. T. Pham, T. Tran, D. Phung, and S. Venkatesh, "DeepCare: A deep dynamic memory model for predictive medicine," in Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), 2016, vol. 9652 LNAI, pp. 30—41, doi: 10.1007/978-3-319-31750-2_3.

19. Hijry, H., & Olawoyin, R. (2021). Predicting patient waiting time in the queue system using deep learning algorithms in the emergency room. International Journal of Industrial Engineering, 3(1), 33-45.

20. Hochreiter, S., & Schmidhuber, J. (1997). Long short-term memory. Neural computation, 9(8), 1735-1780.

21. Olah, C. (2015). Understanding LSTM Networks. colah.github.io.

22. Schuster, M., & Paliwal, K. K. (1997). Bidirectional recurrent neural networks. IEEE Transactions on Signal Processing, 45(11), 2673-2681.

23. Goodfellow, I., Bengio, Y., & Courville, A. (2016). Deep Learning. MIT Press.

24. Rumelhart, D. E., Hinton, G. E., & Williams, R. J. (1986). Learning representations by back-propagating errors. Nature, 323(6088), 533-536.