Enhancing Urban Spaces through Crowd Behavior Analysis

A Case Study of Arafat to Muzdalifah Road During Hajj Time

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Abstract

Crowd behavior analysis is an essential tool for understanding people mobility and movement in public spaces. By analyzing the behavior of crowds and their motion patterns through their interaction with the surrounding environment, designers can identify potential issues and implement solutions to improve safety and efficiency while enhancing urban spaces. The aim of the study is to understand the crowd behavior and movement patterns at the road between Arafat and Muzdalifah during peak times of Hajj to identify prospective overcrowding zones and problems. This has been accomplished through the study use of visual observation, video analysis, and crowd simulation modelling. The study tests the crowd behavior that heavily influenced by the physical urban features, barriers, and surrounding services. The study suggests several recommended interventions for better urban design solutions to improve pedestrian crowd flow for better crowd management. These interventions could be used as guidelines for urban designers and planners to create safer and more efficient pedestrian spaces during similar crowd situations.

Keywords: Crowd Analysis, Urban Design, Crowd behavior, Simulation Modeling, Motion patterns.

1. Introduction

The Hajj is one of the largest gatherings of people in the world, with millions of pilgrims converging on Mecca over a period of several days [1,3]. Crowd behaviors at Hajj time refers to the study of how people move and interact with each other in large crowds during the annual pilgrimage to Mecca at Saudi Arabia. The sheer number of people can lead to safety concerns, as well as logistical challenges in terms of managing traffic flow and crowd movement. To address these issues, researchers study pedestrian dynamics and use computer simulations to model crowd behavior. Through these efforts, they seek to develop strategies for ensuring a safe and efficient Hajj experience for all participants [1,2,4].

In both real and simulated worlds, pedestrian dynamics can be observed and analyzed to gain insights into how individuals navigate their environment and make decisions based on factors such as crowd density, available space, and social norms [5].
In order to better understand how people move around in different situations, researchers can place cameras in public spaces or carry out surveys to analyze pedestrian behavior in the real world.

Analysis of this data can therefore be used to identify potential safety concerns or problem locations as well as to better understand the behavior of crowds in various situations [6, 16]. However, computer simulations that replicate actual conditions make it possible to investigate pedestrian dynamics and crowd motions. Researchers can examine how various factors and situations affect pedestrian conduct using these simulations.

Crowd control is a crucial issue that needs careful planning and oversight during the Hajj period since pedestrian traffic may be analyzed using a range of techniques, including sensor-based systems, video surveillance, video analysis, crowd monitoring devices, and simulation modelling [4, 5]. However, the current issue is that there is a disconnect between the physical construction of spaces, such as the road connecting Arafat and Muzdalifa, and the intended planning or anticipated utilization of such spaces. Despite the use of physical interventions, it is still difficult to manage the crowd, which could result in tragic disasters. There is a need to investigate and combine technical and physical treatments that can improve crowd control in order to produce a safer Hajj experience. By performing research studies that combine qualitative and quantitative analysis, it is possible to identify the dangers and formulate effective crowd analysis techniques with the help of a simulation software [7, 8, 11, 12]. It implies that efficient crowd management requires a thorough strategy that considers elements like the physical environment, the crowd's characteristics, and potential dangers and hazards. [4].

There are several software tools for crowd modelling and management, including both free and paid versions. SimWalk is one of these programs and has a limited number of trials in the context of Hajj experiment [13, 14, 15]. SimWalk software has been the choice to test the accurately level it can predict for pedestrians' movement in and around the Arafat Road area. The test project uses an educational licensed version of the program. By using this tool, work goes to address and detect potential crowd problems providing valuable insights into pedestrian behavior, identifies potential bottlenecks, crowd hotspots, and other areas where design improvements can make a real difference. This software can test different design scenarios and see the impact on pedestrian flow, helping designers to create safer and more efficient public spaces that work for everyone.

Scope of Study and objectives

The journey of Hajj starts with the pilgrims making their intentions and wearing the Ihram at specific locations known as Miqats before arriving in Makkah. There are numerous rites that follow, and they must be performed in a specific sequence. After this, the pilgrims wait for the eighth day of Dhul Hijjah to proceed to Mina. On the ninth day, all the pilgrims move to Arafat and stay there until sunset before proceeding to Muzdalifah, (which is the main focused study area in this research) as depicted in Figure (1). Finally, the throwing of stones is carried out in Al-Jamarat on the 10th to 13th days of Dhul Hijjah [18, 19, 20].

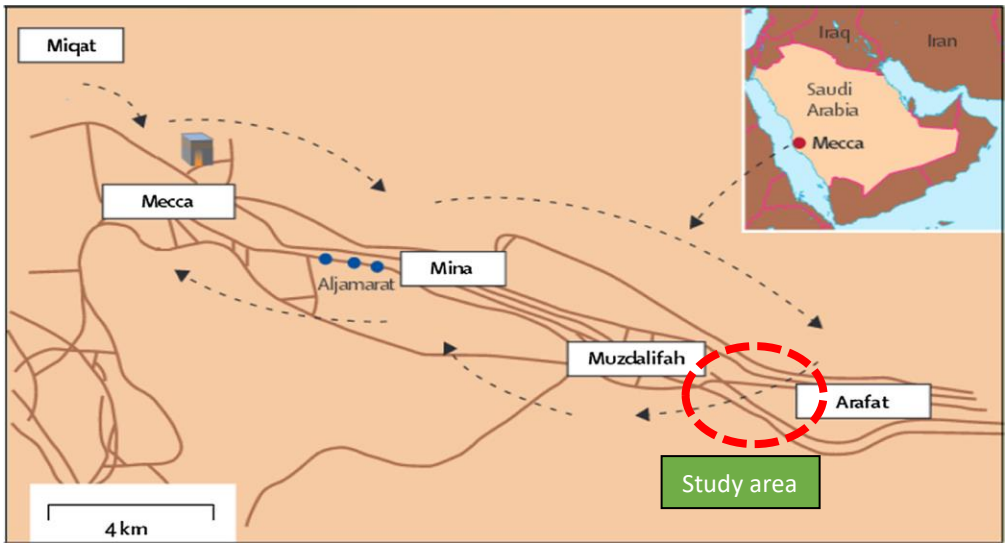

Figure 1: A draft map shows the Hajj journey edited with the scope of the study area [19].

The study aims to use SimWalk software to simulate real-world scenarios and analyze the crowd-related problems that arise on the route between Arafat and Muzdalifah during the Hajj pilgrimage (as shown in Figure 2). By conducting this experiment, the study endeavors to propose effective urban design solutions for the observed problems to address the identified issues and improve the movement of crowds on the road between Arafat and Muzdalifah during Hajj season.

To assess that, a number of objectives have been carried on:

1. Analyze the pedestrian crowd density and characteristics on the way from Arafat to Muzdalifah road during Hajj time.
2. Determine the pedestrian crowd behavior on the selected area.
3. Test the effectiveness of SimWalk software in simulating the real-world scenario of crowd movement during the Hajj pilgrimage.
4. Identify and analyze the crowd-related problems that occur on the route between Arafat and Muzdalifah
5. To propose urban design solutions to manage pedestrian crowds on the studied area during Hajj time including recommendations for crowd control techniques and improvements to urban design.

Figure 2: Map shows the pedestrian street connected from Arafat to Muzdalifah. (Source: Google map scale 1:500, 2023)

2. Methods and Data Resources

To conduct pedestrian crowd analysis during the Hajj time, the study uses a variety of methods, including video recordings, image analysis and pedestrian simulation modelling. These methods can be helpful to identify patterns of pedestrian movement and behaviour, such as crowd density, flow rate, and direction.

A- Data Resources:

The study uses a mixed-method approach, combining both qualitative and quantitative data. The primary data collection method is through observation and statistical data obtained from the Institute of Hajj and Umrah Research, Ministry of Hajj at Makkah city, and a program of studying the movement on the different modes of transportation during the movement from Arafat to Muzdalifah, Saudi Arabia [20]. The observation method involves direct observations for the pedestrian crowd during Hajj time from Arafat to Muzdalifah pedestrian road with the help of fixed cameras as shown in Figure (3). The research then uses analytical approach methodology consists of the following parts:

Study Area:

The selected study area is located between Arafat Mountain and Muzdalifah at one of the parallel pedestrian roads implemented by the government (Rd1, Rd2, Rd4, Rd6) and shares same characteristics. The total length of the road is about 6.5 miles (10 km) between the two destinations (Arafat- Muzdalifah) [21]. As a test project, the research concentrated on a selected section of the road (started by 1 km and had been decreased to about 600m length and 35m width). This would effectively allow test to detect and observe urban elements and pedestrian behaviours as well as identify any problems or areas for improvement during the Hajj time.

Data Collection:

A. The recorded videos were captured on the pedestrian road between Arafat to Muzdalifah during the normal season of Hajj by 2019 for a yearly normal crowd with average number of 2,489,406 pilgrims [22]. According to the data available from the General Authority of Statistics, 2019 was the maximum number of pilgrims over last 5 years shown in Table.1.

Table 1: NUMBER OF PILGRIMS OVER LAST 5 YEARS [22]

2018 -1439	2,371,675	
2019- 1440	2,489,406	
2020- 1441	NA	COVID-19 year
2021- 1442	58,745	
2022- 1443	899,353	

Over the years, specific routes and roads have been established as part of the Hajj infrastructure to facilitate the journey of pilgrims from Arafat to Muzdalifah. While some pilgrims may travel by private vehicles or buses, there are well-maintained roads where most of pilgrims reach Muzdalifah on foot. Two central cameras have been settled in two different positions along one of these roads, capturing videos on both sides. The captured videos have been taken along a whole

day from the morning to the end of the day monitoring pedestrians' movement where the pilgrims moved from Arafat to Muzdalifah.

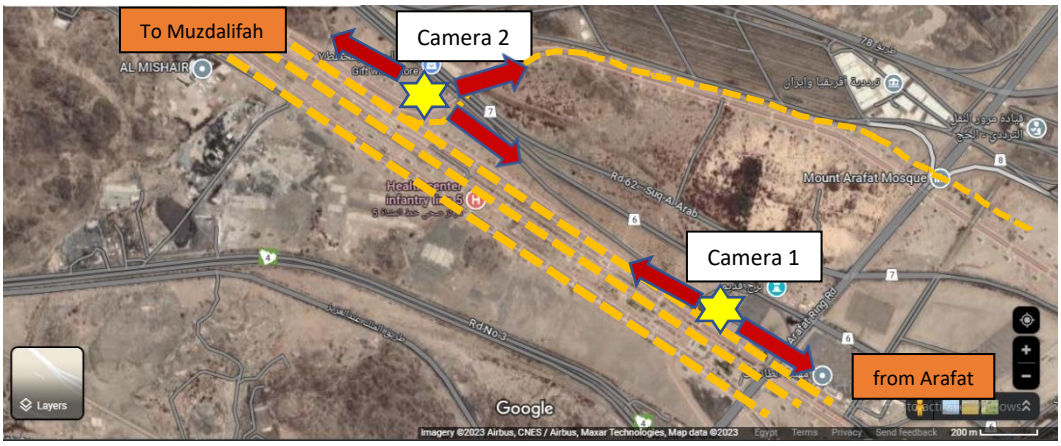

Figure 3: A map shows the cameras' positions to detect pedestrian's movement. (Source: Google map scale 1:200, 2023)

B. Observing pedestrian movement patterns, pedestrian density, and any group characteristics presented in Figure (4) that might affect crowd behavior.

(Data gathered (2019) by the Institute of Hajj and Umrah Research, the Ministry of Hajj in Makkah, and a program to research the movement on various modes of transportation during the journey from Arafat to Muzdalifah, Saudi Arabia [20]).

Figure 4: Data Collected about pedestrians moving from Arafat to Muzdalifah. (Source: Institute of Hajj and Umrah Research, 2022)

C. Compiling information on all the urban aspects and element features that people used while going from Arafat to Muzdalifah. Through last 3 years no new development or changes implemented on the studied road.

By this time, it was simple to observe how pedestrians moved, behaved, congregated, and interacted with all the nearby urban features, as shown in Figures (5, 6), such as water vendors (Figure 9), public restrooms (Figure 7), chairs, benches, and waiting areas (Figure 8), healthcare facilities surrounded by mesh fences (Figure 10), street barriers, and service trucks for nonprofit organizations (charities) that eventually stopped in the road to provide pilgrims with food and water (Figure 11). As depicted in Figure 12, all urban features and services are dispersed along the road. Train exits, however, are not on pedestrian routes.

Figure 5: A map shows position of camera 1 with some services around (scale 1:50, 2023).

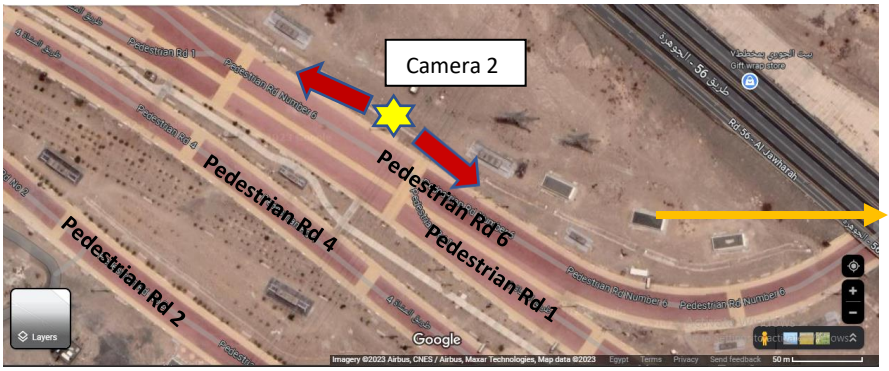

Figure 6: A map shows position of camera 2 with some services around (scale 1:50, 2023).

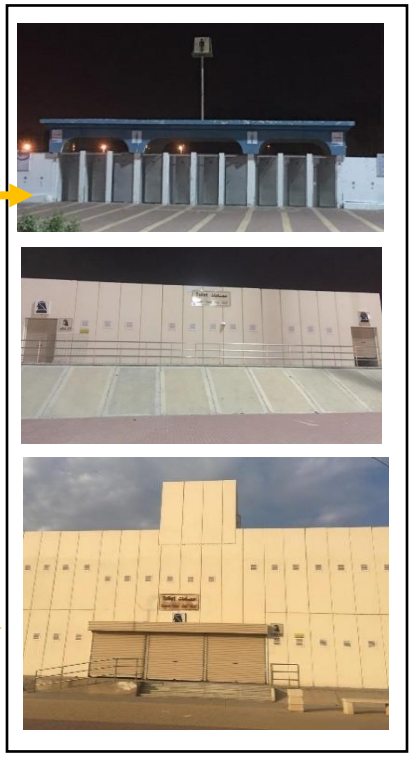

Figure 7: Samples of existing public toilets service [20].

Figure 8: Samples of the fixed redestians chairs that are located along the pedestrians road from Arafat to Muzdalifah [20]

Figure 9: Water vendors stop point provided for the use of pilgrims [20].

Figure 10: HealthCare Center located at the pedestrian road from Arafat to Muzdalifah surrounded by a mesh fence [20].

Figure 11: Movable trucks (Charities) offering water and food charities that stand along the road [20].

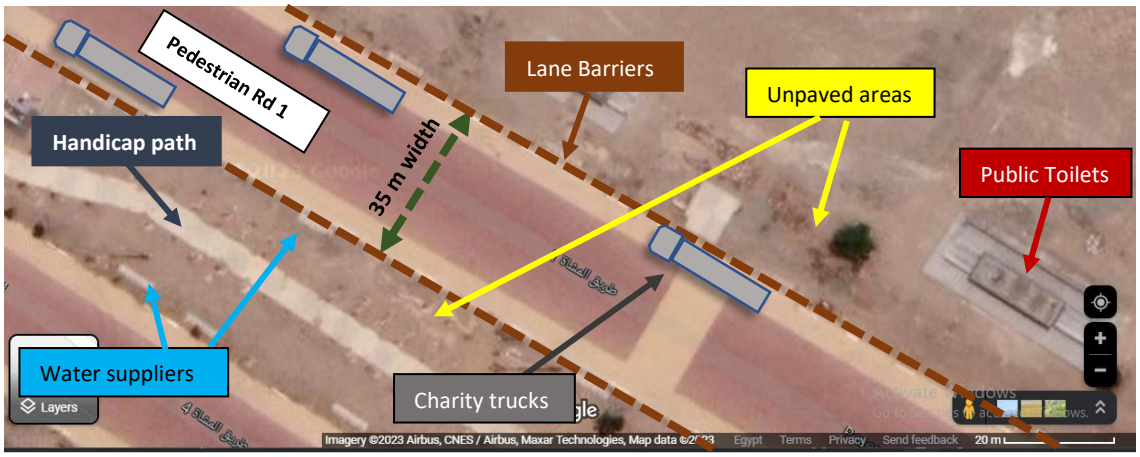

Figure 12: A map shows the exact pedestrian lane with urban features and services around. [Source: base google map scale 1:20, 2023]

D. Pedestrian lane and movement:

When analysing urban areas that are frequently populated by a large number of individuals, such as the area between Arafat and Muzdalifah, it is important to take pedestrian lane and movement into consideration. Due to the large crowds and the significant distance between the two areas, it's essential to have a designated lane that allows for smooth movement and minimizes the risk of accidents or congestion.

In order to analyse the pedestrian movement in this area, it's important to consider factors such as the width and length of the lane (35m width and ≈ 10 km) [21], the number of people moving through it at any given time (500,000 pilgrims/hour) [23], and the speed or flow of the pedestrian traffic (depends on group classification shown in Figure 4). Observing these elements can provide valuable insights into the behaviour of the pilgrims and help identifying any areas where improvements could be made [24].

Overall, studying the pedestrian pilgrims' lane and movement in this area can help inform urban planning and management decisions, with the goal of improving the experience of pilgrims and ensuring their safety and comfort throughout the Hajj time.

Data Analysis:

The research used the recorded videos to analyse collected data by following the next steps:

A. Analyze the collected data from videos with observation along the whole event time to identify patterns and trends in pedestrian flow, shown in Figure (13) with, moderate, and low crowds captured on the road between Arafat and Muzdalifah.

Figure 13: Images for the pilgrims' crowd (a. Moderate crowd with no rush, b. low crowd) captured through cameras settled on the road from Arafat to Muzdalifah, 2019

B. Categorize pedestrian flow into different groups based on their behavior characteristics, depending on data presented in figure (4). This results with a graph show the speed of each identified group as shown in Figure 14. This accomplished with a simple equation (Speed= Distance (10km) /Time)
C. Conduct a statistical analysis to determine the significance of the identified patterns.

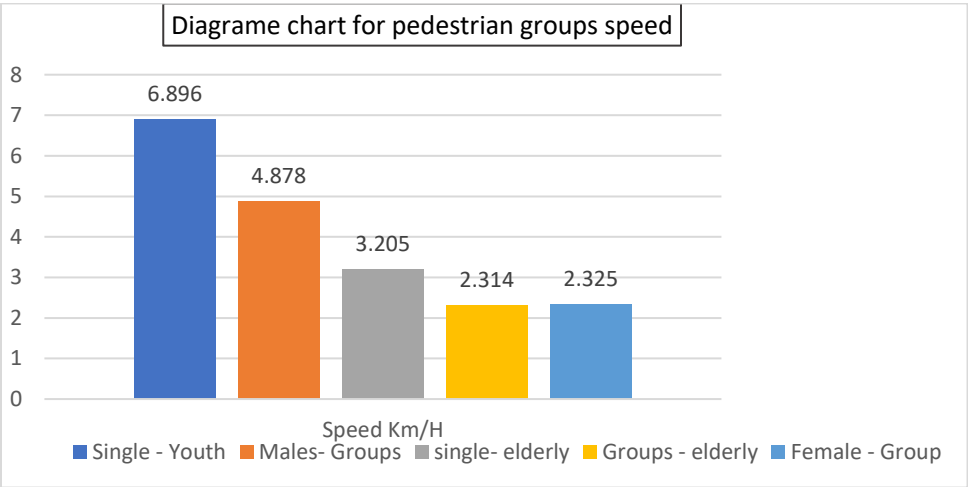

Figure 14: Diagram chart shows the different speed rates for pedestrian groups between Arafat and Muzdalifah street.

Data Simulation

Data simulation techniques are a helpful tool for spotting patterns and trends in data analysis process because they allow researchers and analysts to study circumstances and predict outcomes. It creates a virtual environment that replicates and represents real-world conditions to test different hypotheses and scenarios using software like SimWalk.

For that, the intended simulation elements of the project have been carried out using the following steps:

- All previous mentioned data are necessary for input project's simulation data to work.
- The base map has been created using AutoCAD software for 1 km, however it was then scaled down to 600 m to concentrate more on the urban scale.

- As seen in Figure 15 below, all urban aspects, structures, and services along the roadway have been incorporated into the scenario.
- Several amenities have been added to the settings, including seating places, waiting sections, servicing facilities for water vending machines, and stopping points for charity vehicles.
- The simulation builds the scenario using 6,000 pedestrians (agents) each scene (regarding the educational version limitation). According to camera analysis and the statistics provided, 44% of the pedestrians were female and 56% were male, with an estimated 20% of them using wheelchairs. Additionally, based on data from Figure (4,14), 40% of the participants were categorized as young, and the remaining 60% as old.

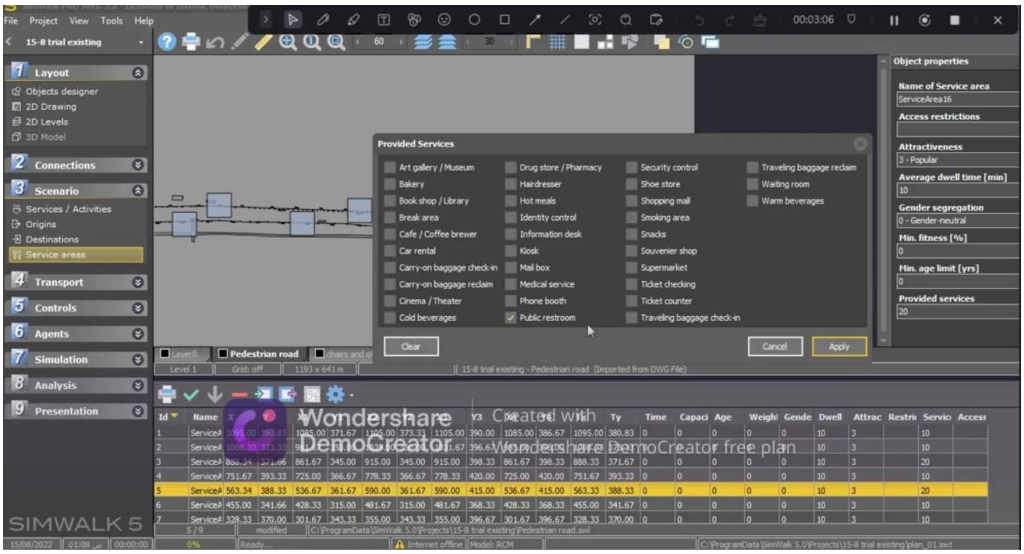

Figure 15: A screen shot from the SimWalk simulation program showing part of the input data entered, 2022.

- All agents have been assigned a route starting from the origin point near Arafat side and ending at the destination going towards Muzdalifah direction as shown in Figure (16).
- The simulation project assign on the SimWalk program to be at the Middle East area, in Summer, using the Social Force model [10, 17] because these factors affect directly agents' walking behavior.

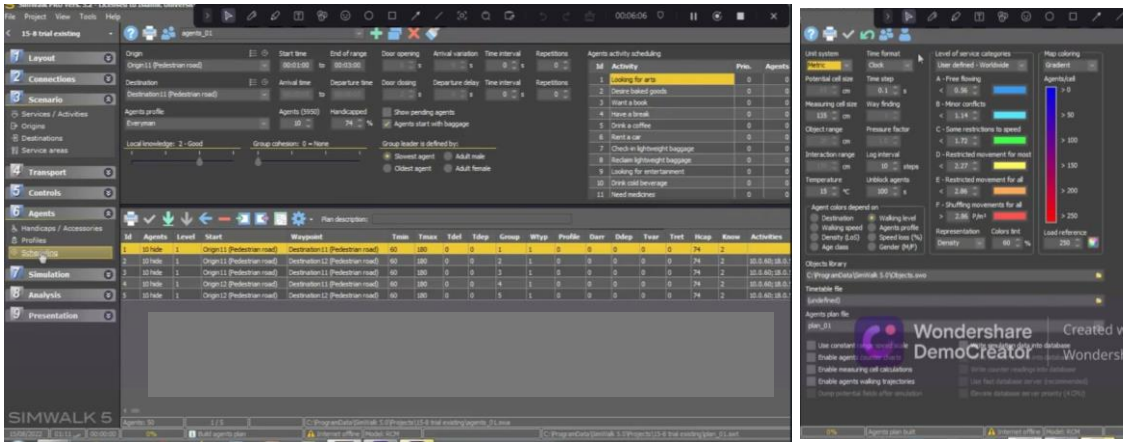

Figure 16: A screen shots for the simulation data entry building the agents data and route, 2022.

B. Model Development:

The model has been developed to the stage of involving the entered data and assigning routes to all agents in the simulation. Specifically, each group of agents have been assigned for a route that started from the origin point near Arafat side, walking through the services on both sides of the road and ended at the destination going towards Muzdalifah direction.

Simulation process:

The pilgrims as agents have been divided into different groups, and each group has been assigned a unique route with activities. The simulation, with the help of a few agents, predicts the number of pedestrians who will pass through the area at any given time. Additionally, by identifying areas of potential congestion or heavy traffic, the simulation, as shown in Figure 17, provides valuable assistance. In reality, allocating these routes ensures that the simulation thoroughly replicates the actual situations.

Figure 17: Two consequence shots from the simulation video on SimWalk program with a total number of 6,000 moving agents, (Source: Author, September 2022)

3. Results

As a test project, the first trial founds SimWalk Simulation to be a useful tool for predicting pedestrian behaviour in a variety of contexts with several types of activities. By altering variables like the time of day, the proportion of groups, or the age groups, simulations can be used to learn insights about how people move and interact in diverse circumstances. To examine the results of this trial simulation, other metrics appear to be resulted for consideration such as:

1. The quantity of out-of-route agents (who take longer routes than necessary to avoid the dense population);
2. The quantity of conjunctions (where agents cross paths, wait for rest, or stop at the charity trucks);
3. The accessibility and availability of pedestrian facilities (such as public restrooms, healthcare facilities, and water venders);
4. the number of uncontrolled agents (who move randomly or without a clear destination).

By analyzing these metrics, it can be identified from the simulation video potential bottlenecks and conjunction areas that needs consideration and improvement as shown in Figure 18.

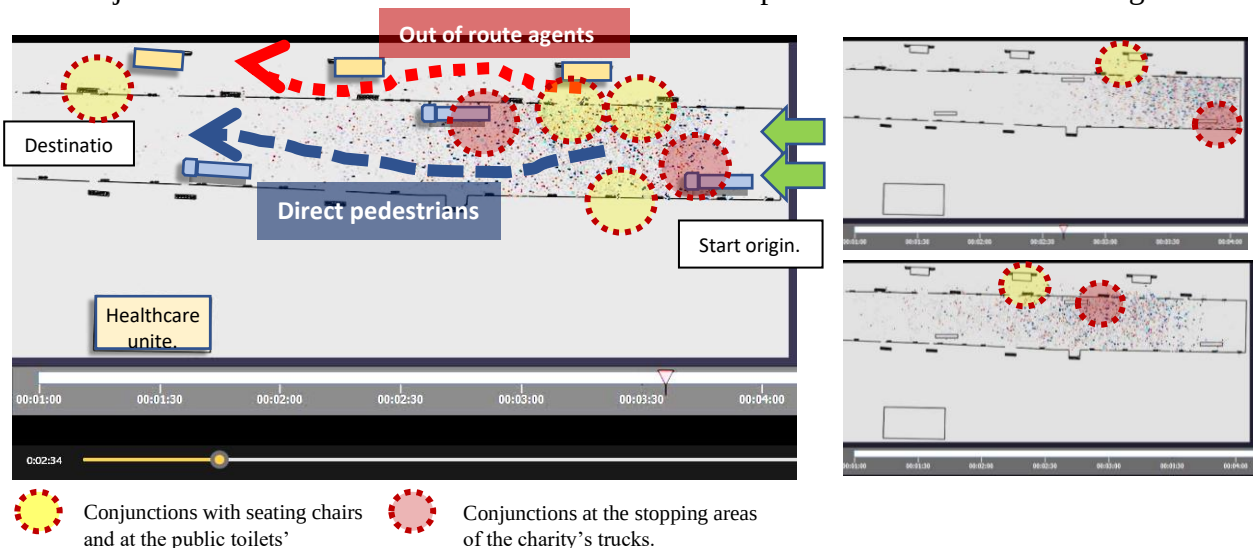

Figure 18: A screen capture of the output video results for the simulation with conjunctions analysis, 2023.

In addition, there are numerous observed variables that can impact the pilgrims' journey in the tested road. These variables and factors that influence pilgrims' movement include:

1. Overcrowding: During Hajj time, the number of pilgrims on the road between Arafat and Muzdalifah increases significantly, leading to overcrowding. This can make movement difficult and increase the risk of accidents.
2. Lack of proper infrastructure: The lack of proper infrastructure, such as adequate lighting, walkways, and rest areas, can also hinder pedestrians' movement.
3. Weather conditions: The weather conditions, especially during the summer months, can be harsh and affect the movement of pedestrians.

4. Discussion

Based on the analysis results of the test project, simulation can extend along the route from Arafat to Muzdalifah to identify potential areas where congestion appears with uncontrolled activities and out-of-route agents. This information can be extremely valuable for identifying these problematic areas where adjustments can be made to the design of crowd movement areas to help alleviate these issues and improve the overall movement of pedestrians. Such trials allow testing various scenarios and fine-tuning the simulation until it precisely replicates the actual behavior of pedestrians. Once this is achieved, it would become possible to modify the design and location of urban features and elements to optimize pedestrian movement and minimize congestion. Therefore, changes to the layout of the road by adding more elements such as benches or shades, or even the implementation of new policies or guidelines for pedestrian traffic would improve the safety and flow of the crowd especially in Hajj time.

Urban characteristics and elements play a vital role in the analysis of pedestrian movement. Effective intervention in pedestrian movement analysis involves identifying and modifying urban features to enhance walkway and solve crowd problems. Some of the urban characteristics and elements presented in Table (2) below, could have a significant impact on pedestrian crowd movement design of the studied road.

Table 2: illustrates several variables with problems description and suggestions for design intervention:

Level of intervention	Variables	Problem description	Suggestions for design Intervention
Roadway Urban Characteristics	• Sidewalk	Narrow sidewalks can result in congestion and slow the movement. Pedestrians walk out of the roadway.	Widening sidewalks can help to increase pedestrian flow and minimize congestion. Pedestrians path clearance from any obstacles.
	• Street Furniture	such as benches and trash cans can impede pedestrian flow. Pedestrians sometimes used to set on ground regarding the low number of benches.	Relocating them first out of the main pedestrian flow and then increasing their number can improve pedestrian movement. It would be better to change the metal material of the chairs to a more suitable one, especially in hot weather countries.
		Water venders are along the way on both sides destructing the barriers.	Water venders already existed on both sides of the road.
	• Services building Entrances: public toilets, healthcare units.	Large building entrances that open directly onto the sidewalk can impede pedestrian flow.	Relocating entrances or creating vestibules, direct clear approach can help to improve pedestrian movement.
	• Road Barriers	Concrete barriers are located on both sides with openness.	Better to decrease the openness with exception in front of exits and services buildings or think in new technique.
	• Charity Trucks	The trucks stopped on both roadsides causing	Moving away the trucks to be off roadway with a service lane would

		main conjunctions in the flow.	improve the pedestrian's movement flow.
	• Exits for train station, bus stops.	Not clear in plan level or even in observation	Exits signs should be clearer with more adequate approaches
	• Green spaces and shades	Greenery is limited with no shading areas.	Increase green spaces and elements such as Palm trees would sure add shaded areas along the way. Shade elements can play a valuable role especially over chairs and waiting areas.

Depending on the observed variables, there are several interventions that can be made in the development stage to improve pedestrians' movement and crowd behavior on the road between Arafat and Muzdalifah during Hajj time includes suggestions of:

1. Increase the capacity of the road: The road between Arafat and Muzdalifah should be designed to accommodate the increasing number of pilgrims during Hajj time.
2. Implement a one-way system: A one-way system can be implemented on the road to improve the flow of pedestrians and reduce traffic congestion. This can be achieved by dividing the road into different lanes for pedestrians and ensuring that pilgrims move in the same direction.
3. Clearing the roadway from charity trucks is preferable. It could be on a separate lane besides.
4. Create rest areas: Rest areas can be modified and increased in number along the road between Arafat and Muzdalifah to provide a place for pilgrims to rest and recover. These areas can be designed with seating, water venders, and public toilets to provide basic amenities for pilgrims.
5. Providing clear signage: Clear signage would help to direct pedestrians to their destination and reduce confusion. This would also help to prevent congestion and improve the flow of pedestrian traffic.
6. Enhancing lighting: Improving lighting along the roads and walkways would increase visibility and improve safety for pedestrians, particularly during nighttime hours.

Applying these guidelines and interventions on a design trial would help to improve the design layout of existing road for better safety and efficiency movement expectations.

5. Conclusions

The study on pedestrian crowd analysis between Arafat and Muzdalifah during Hajj time with the help of pedestrians' simulation software has revealed key insights that can inform better urban design solutions. By analyzing pedestrian behaviors, movements, and densities, this study highlights the importance of prioritizing pedestrian safety, efficiency, and comfort in urban design. By using advanced technologies, it is possibly understanding how pedestrians interact with their environment and make informed decisions to improve urban planning. SimWalk software has been used to help in simulating and visualizing pedestrians' movement for better understanding the behaviors and characteristics of pilgrims' groups during Hajj.

Therefore, the implementation of suggested solutions could enhance the overall urban experience for pedestrians and improve the city's functionality, safety, and sustainability.

Finally, future recommended research could extend to examine the suggested interventions with several simulation scenarios and compare different software programs to explore the impact on the crowd flow and evaluate their effectiveness and sustainability.

Acknowledgment

The SimWalk team deserves much appreciation for their valuable support during the research project. A special thanks goes to Alex Schmid from Savannah Simulations AG. Acknowledgement goes for the contribution of Dr. Sadeq Kadi at Saudi Arabia, for providing insightful data sources and helping with recorded videos. Additionally, a deeply grateful for the Institute of Hajj and Umrah Research, Ministry of Hajj at Makkah city for providing quantitative data.

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