Regional Science Policy & Practice 17 (2025) 100179

Contents lists available at ScienceDirect

Regional Science Policy & Practice

journal homepage: www.sciencedirect.com/journal/regional-science-policy-and-practice

Location models to improve health and safety at a major temporary city: The case of the Hajj

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ARTICLE INFO

Keywords:
Location planning
Location-allocation models
Agent-based models
Temporary cities
The Hajj

ABSTRACT

This paper investigates the optimal locations of health service facilities during the Hajj, a major temporary city event in Mina, Saudi Arabia, attended by millions of pilgrims. Given the logistical challenges and historical accident risks during this dense gathering, effective placement of health facilities is crucial for ensuring pilgrim safety and accessibility to services. The study first employs location-allocation models (LAM) within a network GIS framework to determine optimal facility locations based on both static and dynamic population distributions of pilgrims throughout the day. These models facilitate the strategic placement of services closer to pilgrim activities, potentially enhancing service accessibility and reducing travel times for medical assistance. Additionally, agent-based modelling (ABM) complements the LAM by simulating crowd movements and interactions, helping identify high-risk areas for congestion and accidents. This dynamic approach offers insights into crowd behavior under various scenarios, including different times of day and road closure impacts, thereby supporting more responsive urban planning and crowd management strategies. Recommendations for policy include the use of portable health facilities and the strategic placement of services to accommodate shifting crowd densities.

1. Introduction

There is growing interest in urban geography and planning on temporary city space. Temporary urban spaces most often include sites for festivals, exhibitions, public gardens or even car parks (Bishop and Williams, 2012; Madanipour, 2018). However, in some rarer cases, entire cities can be classified as temporary. One example is the Hajj religious festival for Muslims, described as the largest gathering of people to take place on an annual basis. The Hajj, in the city of Mina in the eastern district of Makkah city in Saudi Arabia, (see Fig. 1.1) takes place over a period of just 6 days but has to accommodate around 2.5 million pilgrims in a so-called tented city. Pilgrims can be both national and international. To cater for that many people the city extends over 20 sq. km.

Setting up the Hajj each year presents huge logistical challenges. Most importantly, there is a need to ensure safe access to good quality urban services. Planners need to ensure that consumer services (such as health, security, fire services etc.) are located in the most convenient, accessible places. There is also an urgent need for high standards of crowd control and management. Table 1.1 lists a number of accidents that have occurred during the Hajj and resulted in major injuries and deaths. Large crowds moving from their accommodation sites to the main location where the religious rituals take place (Jamarat Bridge) produces opportunities for congestion and consequent crushing and stampeding.

There are two principal aims of this paper. The first is to examine the optimal locations for health services in the temporary city of Mina and to compare these with the current distribution of facilities. This will be undertaken in relation to both the location of pilgrims in the tented city at night and during the movement of the pilgrims towards the Jamarat Bridge during the day. The main methodology employed here will be location-allocation models within a network GIS framework. The results of various what-if scenarios will be compared against the current location of services. A major argument will be that planners should be flexible and locate facilities at different locations throughout the day and night. The use of location-allocation models in this type of dynamic mode is not commonly seen in the literature (see Section 2 for more discussion). The second aim is to model the crowd movements and behaviours along the most congested parts of the network in detail. This will be explored using both network GIS and an agent-based model. The crowd model will enable planners to see at what stage in the movements of pilgrims problems occur in terms of potential crushes and trampling

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https://doi.org/10.1016/j.rspp.2025.100179
Received 19 June 2024; Received in revised form 12 January 2025; Accepted 18 January 2025
Available online 27 January 2025

Fig. 1.1. The geographical location of Makkah city, Mina, Muzdalifah and Arafat areas (source: Al-Kodmany, 2009).

Table 1.1
Major historic disasters at the Hajj (nb stampeding=intentional pushing; trampling=unintentional crowding).

Reason	Event	Location
Stampede	July 2, 1990: A stampede inside a pedestrian tunnel leading out from Makkah towards Mina and the Plains of Arafat led to the deaths of 1426 pilgrims.	Almaaisim Tunnel (Mina)
Stampede	May 23, 1994: A stampede killed at least 270 pilgrims at the stoning ritual	Jamarat Bridge (Mina)
Fire	April 15, 1997: There were 343 deaths and more than 1500 estimated casualties in the tented city (Ahmed et al., 2006).	Tented City (Mina)
Stampede	April 9, 1998: 118 pilgrims were trampled to death and 180 injured in a crushing incident	Jamarat Bridge (Mina)
Trampling to death	March 5, 2001: 35 pilgrims were trampled to death in a stampede during the stoning ritual	Jamarat Bridge (Mina)
Stampede	February 1, 2004: 251 pilgrims were killed and another 244 injured in a stampede during the stoning ritual in Mina.	Jamarat Bridge (Mina)
Stampede	January 12, 2006: A stampede during the ritual Ramy al-jamarāt on the last day of the Hajj in Mina killed 345 pilgrims and injured 1000.	Jamarat Bridge (Mina)
Crush due to pedestrian collision	September 2015: 717 killed and many injured in a crush outside Makkah.	Road 204 (Mina)

incidents. The question is focused on how crowds at the Hajj can be managed to avoid collisions and bottlenecks and, if these happen, how they can be detected in their early stages to prevent escalation.

The paper is organised as follows. In Section 2 we briefly review the main modelling methods to be used and their relevant applications. Section 3 shows the study area in more detail and explores the use of GIS and location-allocation modelling for planning health services optimally. In Section 4 we combine this analysis with the results of an agent-based model. Concluding comments are offered in Section 5, especially in relation to policy recommendations.

2. Modelling methods

This section will review the two primary methods used in the remained of the paper: location-allocation modelling (Section 2.1) and agent-based modelling (Section 2.2).

2.1. Location-allocation modelling

For planners and decision makers alike, facility location has always been a critical aspect of urban design (Hodgson, 1978; Owen and Daskin, 1998). Locating individual service outlets in an optimal fashion has become important for allowing visitors to reach facilities easily and cheaply. The location allocation model (LAM) is a well-known tool to help decision-makers to find best locations to operate services from. LAM can be defined as the simultaneous location of central facilities and the allocation of services based upon the dispersed demand to them. The locations determined by LAM are the optimum amongst other choices of possible locations. The models start with a population (or demand) located across a spatial area, usually in census tracts or zones. Then, service facilities can be located optimally in relation to that demand. The planner or system engineer can decide the number of facilities to be located and these are found by the model via minimising the distance travelled to that chosen number of facilities across the study region (although other criteria can be included). Excellent reviews and summary of progress in this field appear in Tomintz et al. (2015), Tong and Murray (2017), Murray (2010, 2021). There are also a number of excellent reviews which compare location-allocation models with other types of optimisation models for facility planning, illustrating the pros and cons of each (see for example, Ghosh and Rushton, 1987; Mamoun et al., 2021; Ayati et al., 2024)

In the public sector, applications have related to parks, public schools, military bases, police stations, radar installations, shopping centres, libraries, branch banks, post offices, hospitals, waste-disposal facilities and public buildings. The models have also been applied in the private sector,. However, when these models are used in the private sector the aim is normally to maximise profit and market share rather than minimise consumer travel times (Marianov and de la Figuera, 2004; Goodchild, 1984). Interesting applications of LAM in relation to health care facility location, that are relevant to this study in particular, appear in Kemboi and Waithaka, (2013), Polo et al., (2015), Murray and Grubesic, (2016), Gulzari and Tarakci, (2021). In addition to these models, which generally allocate health facilities for an existing population, Santana and dos Santos (2024) show how variations in health facility locations (and hence different accessibility surfaces) can impact morbidity and mortality whilst Sass and Porsse (2021) show the need for new facility locations given urban sprawl and a growing urban population. Given our concern for pilgrim movements and walk-in health centres, Taymaz et al. (2020) provide an interesting study of optimal locations for walk-in health centres along long distance transport routes in Africa (especially to cater better for truck drivers).

The use of the location allocation model for optimisation is often subject to a set of criteria or constraints. Hakimi (1964) was the first author to define the p-median model. To solve the p-median problem, the following data are required:

- Number of possible supply locations.
- Number of demand zones.
- Distance (time or cost of travel) from each demand site to each potential supply location.
- Number of facilities to open

Fig. 3.1. The tented city in Mina.

The objective function for the p-median problem can then be stated as follows:

$$minimise Z = \sum_{i\in I}\sum_{j\in J} a_i \quad d_{ij} x_{ij}$$

Subject to the following constraints:

- An individual demand to be assigned to a facility $\sum_{j\in J} x_{ij} = 1$ for all i.
- Demand must be assigned to an open facility $x_{ij} \leq \sum x_{ij}$ for all (i, j).
- Exact p facilities have to be located: $\sum_{j\in J} x_{jj} = p$.
- All demand from an individual site of demand is assigned to only one facility.
- $x_{ij} = (0, 1) \textit{ for all} (i, j)$.

In this equation, z represents the objective function; I is the set of demand areas and the subscript *i* is an index denoting a particular demand area; J is the set of candidate facility sites and the subscript *j* is an index denoting a particular facility site; a_i is the number of *people at demand site i; d_{ij} is the distance (time or cost of travel) separating place i from candidate facility site* j; x_{ij} is 1 if demand at place *i* is assigned to a facility opened at site *j* or 0 if demand at place *i* is not assigned to that site; p is the number of facilities to be located.

As seen above, in this paper we are locating facilities purely based on distance minimisation. There are many studies which use additional variables to fix locations. For example, Fortney (1996) added user preferences (or choices) based on a variety of additional factors in addition to cost minimisation. Similarly, other studies have used a variety of variables (multiple levels of data) to add to distance minimisation. Leitch and Wei (2024) chose a variety of variables related to equity and efficiency, whilst Quinta-Nova and Ferreira (2024) use GIS and spatial models to also add a variety of factors to decide the optimal locations.

Most location-allocation models estimate a static demand base from which to locate facilities optimally. However, there is a growing interest in defining demand at different times of the day or week. Good illustrations are provided by Lin (2014), Duhamel et al. (2016), Ankrah et al. (2019) and Karatas (2021), whilst Nasrabadi et al. (2020) consider short-term and long-term location planning. We build on that literature for the demand estimates below.

2.2. Agent-based models

An agent-based model (ABM) is a modelling tool that simulates the movements of individuals based on certain behavioural rules, exploring the outcomes of the interactions between many discrete 'agents' (Bonabeau, 2002). In terms of their applications, ABMs have contributed to many disciplines, such as informatics, sustainability science, computer science, ecology, transport studies, anthropology, economics, crime analysis, political science, urban studies traffic and air traffic control (good reviews appear in Macal and North (2010), Torrens (2010), Abar et al. (2017), Crooks et al. (2008, 2015, 2021), Malleson et al. (2022)).

ABMs have certain merits such as flexibility in the representation of human and dynamic phenomena, facilitating the exploration of ideas and approaches developed and viewing behaviour and interactions with geographical systems (Bonabeau, 2002; Torrens, 2010). It can be argued that ABMs represent a shift in the social sciences and especially in individual-based fields (Malleson et al., 2010). Although there are numerous other micro models available to the researcher ABMs are particularly well suited to individuals moving through networks and reacting to the behaviour of other agents. However, for the interested reader, Ballas et al. (2019) compare the pros and cons of ABMs in relation to microsimulation models, whilst Clarke (2021) provides a good review of ABMs and cellular automata models. Vermuyten et al. (2016) provide a good review of (micro) optimisation models for pedestrian evacuation and design problems.

Although the methodology has been widely used in different disciplines, there remain some limitations. Some element of arbitrariness is implicit due to the perceived need to represent the world in as rich a manner as possible (Crooks et al., 2008). A long-standing problem with ABMs is that there is often a lack of theory from which to derive rules to drive the behaviour of the agents (Torrens, 2010). Further, researchers can encounter obstacles related to data and software to support the development of ABMs. The ABM needs to be related to real-world data and, where possible, be calibrated using the results for real units of movement and distance. Despite these limitations, ABMs have already shown great potential for use in studies related to pedestrian movements, crowding issues and evacuation planning. If the modeller re–creates some scenarios within a model, it becomes easier to identify potential problems in systems, such as bottlenecks and pedestrian movement patterns, or to discover implications for evacuation time (Liebig and Wagoum, 2012; Torrens et al., 2012).

There have been a number of ABMs built to look specifically at crowding behaviour at various religious festivals around the world. In Makkah, Sarmady et al. (2007) used multi-agent based models to simulate the crowd during the 'Tawaf'. The properties of agents used in

Fig. 3.2. The Jamarat Bridge where the stoning ritual takes place.

the model were; gender, age, orientation or way finding capabilities, energy, health levels, tiredness, desired speed and stress level. The description of their inbuilt ‘pushing behaviour’ is very critical and realistic, since if pilgrims cannot maintain enough distance in front of them against others, due to the tiredness of those in front of them, they will keep pushing to try to speed up others. However, if this degree of pushing is exaggerated, this might lead to the pilgrims in front falling down or being crushed against walls, or if shorter than others, they might be asphyxiated.

There have already been a number of interesting ABMs built for application at the Hajj, although these have been primarily concerned with reducing congestion on the Jamarat Bridge. Fayoumi et al. (2011) conducted research to simulate pedestrian movement during the stoning ritual that occurs at the Jamarat. They used an ABM called ‘STEPS’ to optimize people’s movement while throwing stones. In the same area, Rahman et al. (2015) developed a similar approach to accommodate a larger number of pilgrims. Similarly, Ilyas (2013) build a simulation to evaluate throughput, peak load and safety of pilgrims stoning the devil, but again his study is limited to the bridge only. The author found that the optimal queuing time for pilgrims during the stoning procedure resulted in an elliptical shape of Jamarat pillars, which is the shape adopted when building the new version of Jamarat Bridge. Al-Kodmany (2013) analysed the crowd incident on 12 January 2006 and pilgrims’ movement during the Hajj ritual. The analysis revealed that deaths and serious injuries began about 10 minutes after the onset of ‘turbulence’ and 30 minutes after the onset of ‘stop-and-go’ flow. An interesting insight was provided into how urban design scenarios can be tested and what alternative solutions can be applied in the crowd management field. As a consequence, the Saudi government has implemented automated counting of pilgrims to give a reliable overview of density and capacity conditions in critical places in the Hajj ritual.

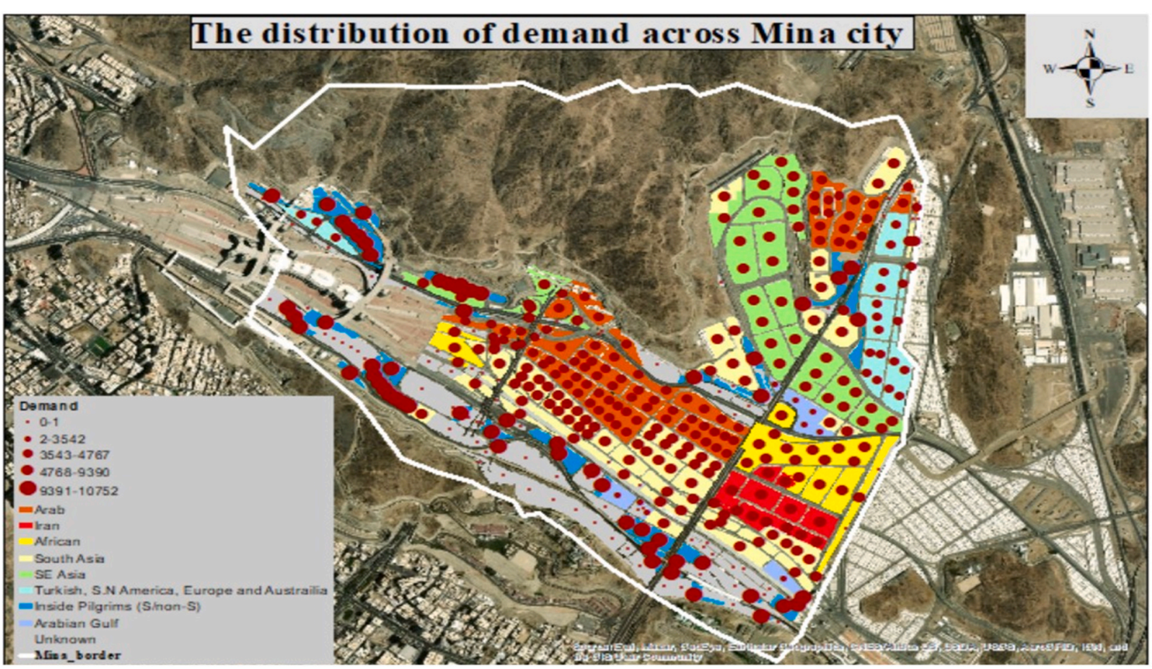

Fig. 3.3. Population based on the night-time population.

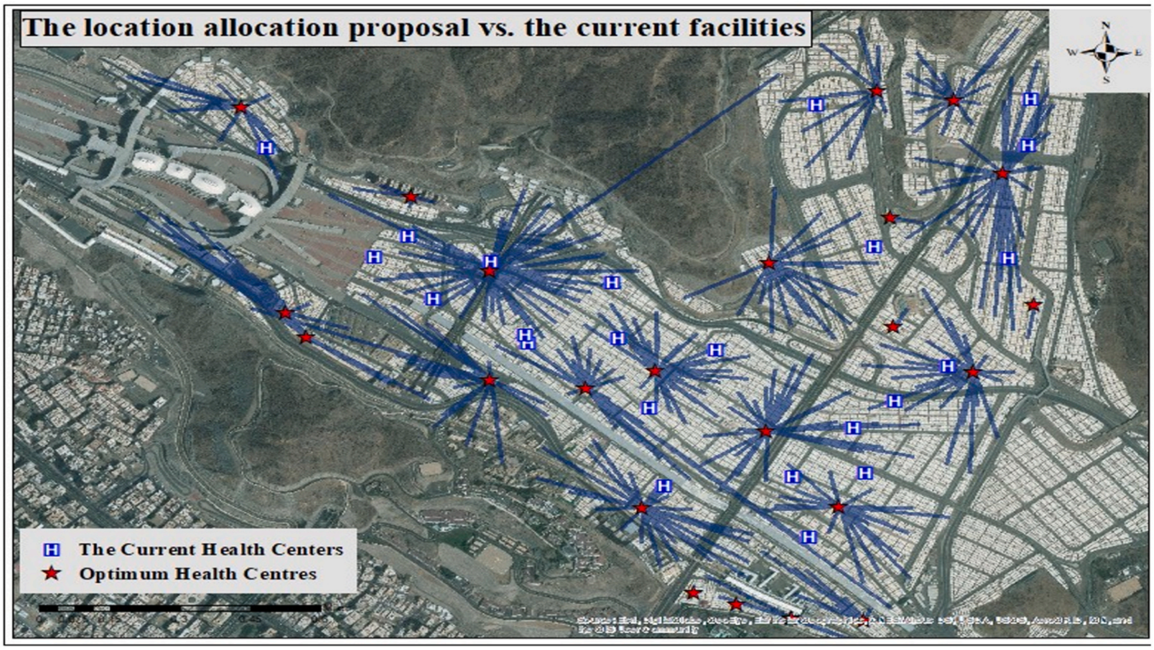

Fig. 3.4. Optimal v actual locations based on night-time population.

Table 3.1
Numbers of pilgrims in different accessibility bands for current and optimal health centre locations.

Distance	POP/ current health centres	POP/ optimum health centres
0-150 m	210,081	275,917
150-300 m	516,389	840,388
300-450 m	705,765	670,304
450-600 m	479,958	423,763
600-750 m	175,660	192,470
750-900 m	231,183	68,543
900 M +	170,379	18,030
total	2,489,415	2,489,415

3. GIS and location-allocation modelling within Mina

Mina is located in a low-lying valley in the province of Makkah (see Fig. 1.1). Its climate is hot, with low rainfall levels, and has a high probability of sand storms and dust in the summer and dry, but cooler winters. The so-called tent city built to accommodate the pilgrims can be seen in Fig. 3.1. The tents are neatly distributed and organised in rows. Every camp is colour-coded and numbered by country and based on that code pilgrims are issued with badges with their colour and number to guide them if they become lost (Kaushik, 2014). These tents form a place for pilgrims to take rest during the Hajj season. For the rest of the year, Mina remains almost deserted. More details of the Hajj festival itself can be found in Al-Kodmany, (2009), Tagliacozzo, Toorawa (2016) and Peters (2021). Pertinent to this study, a number of studies have specifically examined health issues at the Hajj. For example, Noweir et al. (2008) considered the impacts of heat exposure on pilgrims, especially as elderly persons walk to Jamarat Bridge. Ahmed et al. (2006)

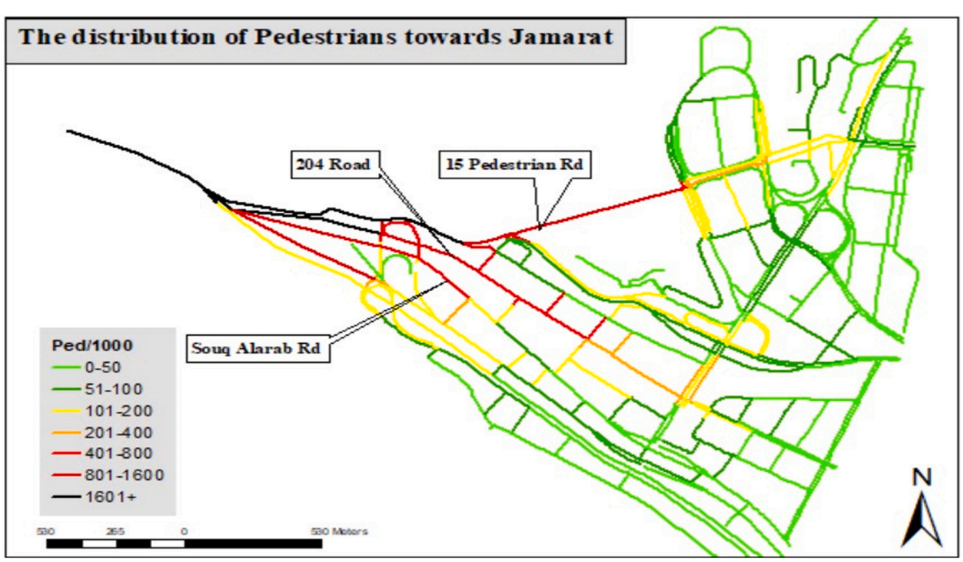

Fig. 3.5. Allocating pilgrims along the pedestrian road network to the Jamarat Bridge.

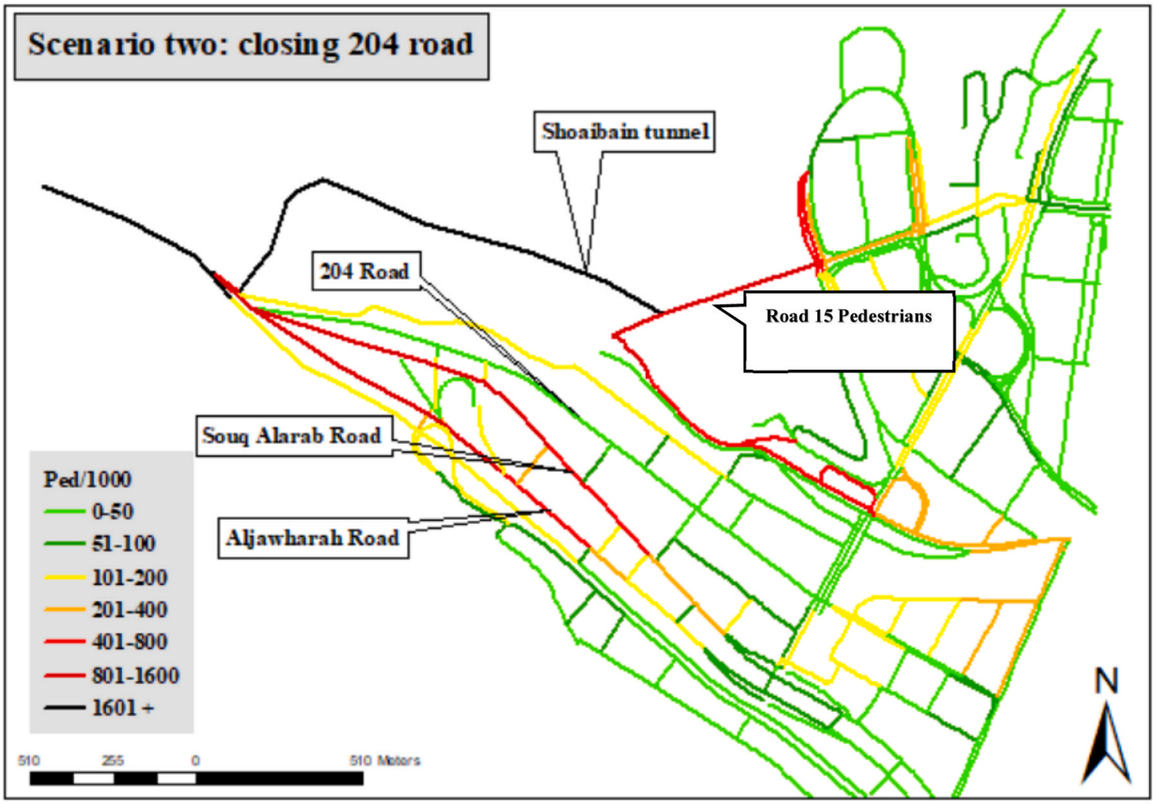

Fig. 3.6. Congestion builds on surrounding roads when 204 Road is closed.

examined broader aspects of health concerns including the dangers of contagious disease spread given the close contact of pilgrims throughout the Hajj. Al-Rashed (2003) looked beyond the use of health centres for minor ailments and fatigue by exploring hospital admissions throughout the festival.

Fig. 3.2 shows in more detail the area to the far north of the tented city seen in Fig. 3.1 and the location of the Jamarat Bridge where the pilgrims undertake the main ritual of the Hajj – the stoning of the devil.

For the analysis which follows it was first necessary to build a GIS containing the population as a demand surface and the road network (from the tented accommodation to the place of the ritual stoning – the Jamarat Bridge). Fig. 3.3 shows the known population distribution based on the tented city.

Given the location of this population (the demand in the LAM) we

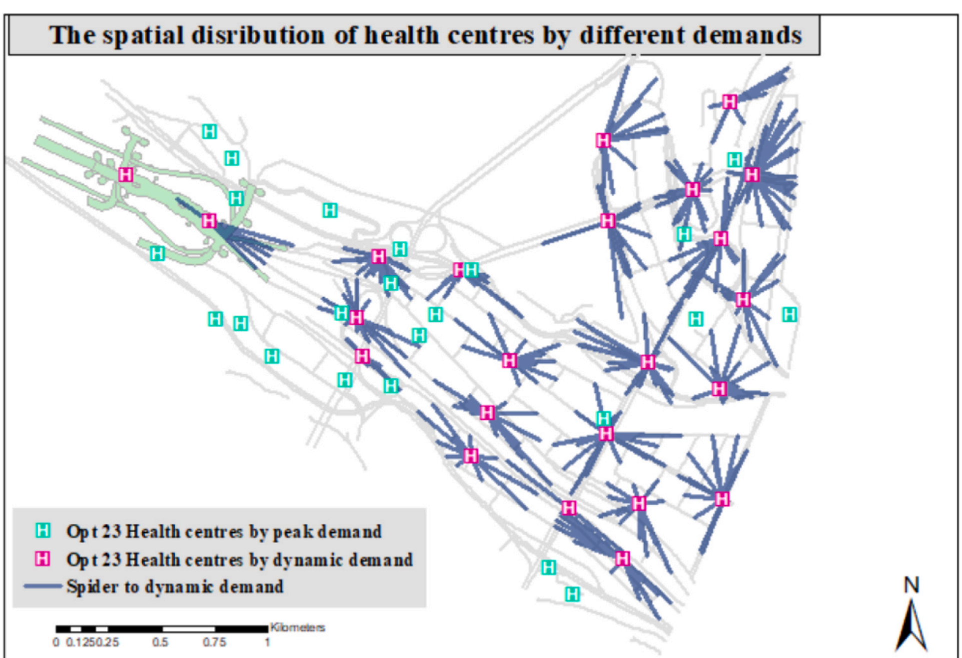

Fig. 3.7. Optimal v actual locations with a transient population.

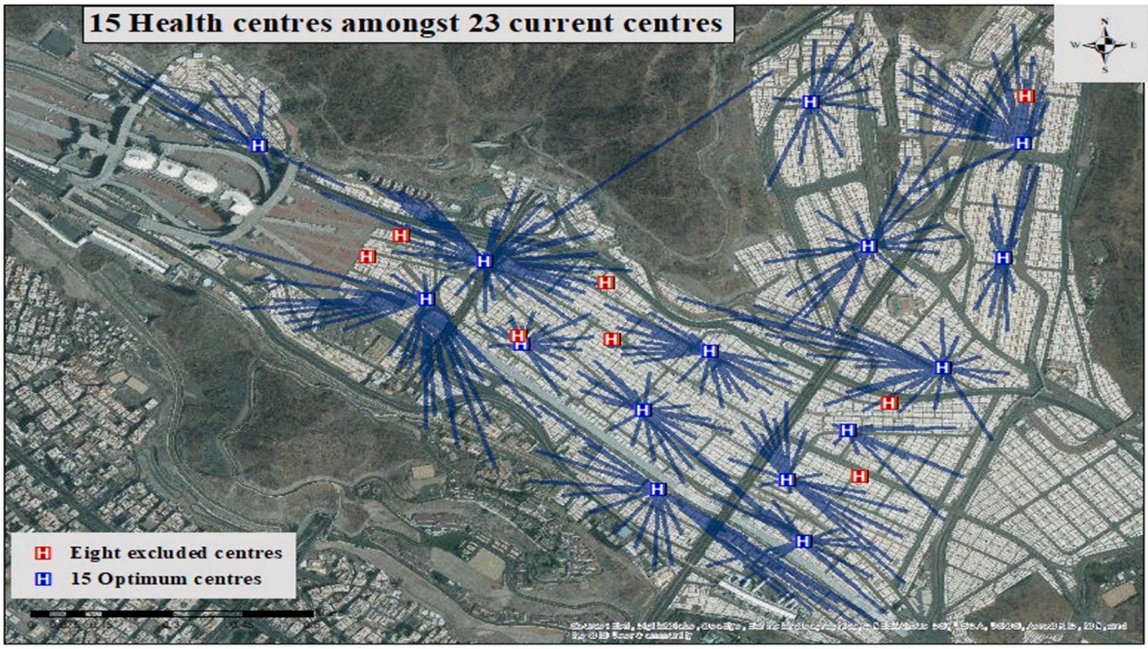

Fig. 3.8. Model-based optimal locations (v actual) for 15 health centres.

now compare the results of the LAM with the actual distribution of health centres (Fig. 3.4). The patterns show a reasonable similarity, but that the model wants to put many more facilities to the south of the region where many workers live during the Hajj. As can be seen, they are currently very poorly served for access to health care.

The resultant increase in accessibility for the new configuration of centres can be seen in Table 3.1. This shows the improvement in the number of persons now in the low distance/high accessibility bands (compare pop/current with pop/optimum) but also the reduction of numbers in the higher distance brackets too. Thus we now see a significant increase in the numbers of people within 500 m of a health centre and many fewer in the 750 m plus.

However, Fig. 3.4 also shows that the optimal solution when using the night time population fails to adequately cover pilgrims on the move (which the actual distribution presently does to some extent). Thus, to provide a better solution we need to distribute the demand from the origin tented locations across the network, to mimic how pilgrims move towards the Bridge and where they may be at certain times of the day. To do this we derive the shortest distance from an origin point to the Bridge and allocate the pilgrims along the network accordingly. This uses the shortest path algorithm in Arc Info. As the pilgrims set off from their night time locations we count the flows along the road networks so that any for any particular time of the day we can now estimate the transient population and the numbers within each road segment. Fig. 3.5 shows the results of this process. In effect, we have estimated a dynamic demand, moving the residential population from its base location in the morning towards the bridge, culminating in most pilgrims arriving at the Bridge between 12 and 2 pm. In theory, we could plot the demand at any hour of the day.

Fig. 3.5 shows that the routes become very congested near the approach to the Jamarat Bridge as individual feeder roads meet. Given the improvements made by the authorities over the last few years to the approach roads to Jamarat Bridge, the highest values near the Bridge (the black routes) are not deemed to be a major problem. However, Fig. 3.5 highlights three potential roads which are more likely to be problematic each carrying between 400,000 and 1.5 million throughout the day. We shall return to this issue in Section 4.

Having built the network model it is now possible to undertake any number of what-if scenarios. A common problem at the Hajj is temporary road closures. This might come about as the result of a minor accident (or even a major incident) or simply to undergo temporary repairs. Fig. 3.6 shows the results of a temporary road closure to 204 Road as an example. The map shows how much more congested the routes around 204 Road become when it is closed and the pilgrims are effectively re-routed. This is important information for planners – the ability to predict the impact of enforced road closures is crucial.

We can now use this new dynamic demand layer to produce a new set of optimal locations in the model. Fig. 3.7 shows the results of the model rerun with the more dynamic demand along side the peak demand (as shown the estimation is that about 70 % of the pilgrims are in the sector close to the Bridge around midday in the case of Peak demand). Fig. 3.7 shows how many more health facilities are now located by the model along the main pathways, making the model results more realistic and useful to planners (in the case of the dynamic demand). Given that the night and day time model-based locations are very different, a strong policy recommendation is to have more portable health facilities, shifting care from the tented city at night to the health centres recommended along the network during their travels. This might be a more expensive option than employing static health facilities but it would allow much greater accessibility throughout the day, ultimately serving the population of pilgrims and workers more effectively.

Once built the modelling system again allows the analyst to perform various what-if scenarios. For example, it is understood that the authorities are keen to reduce costs, as the costs spiral each year. Fig. 3.8 shows a cost-cutting exercise where we ask the model to allocate 15 rather than 23 centres. This obviously reduces accessibility across Mina as a whole but if planned carefully the impacts of that reduction can be minimised.

4. Simulating crowd movements with an agent-based model

The next part of the exercise is to look in more detail at the specific local implications of the movement of pilgrims. To do this we employ an agent-based model (ABM). PTV Group (Planung und Transport Verkehr AG) have developed the VISSIM program to simulate vehicle traffic and pedestrian movement (Lagervall and Samuelsson, 2014; Wibowo and Fadilah, 2018). VISWALK is an add-on module to VISSIM to simulate large numbers of pedestrians, either inside buildings or outside.

Table 4.1
The FRUIN classification.

Fruin Walkway LOS					
	Ped/m/min	Ped/min/m	Ped/m^2	Side Size (m)	Flow Condition
A	<23	<7	0.08	1.93–1.80	Free flow
B	23.0–32.8	7–23	0.08–0.27	1.80–1.67	Minor conflicts
C	32.8–48.2	23–33	0.27–0.45	1.67–1.52	Slower speed
D	48.2–65.6	33–49	0.45–0.69	1.52–1.36	Restricted most
E	65.6–82	49–82	0.69–1.66	1.36–1.18	Restricted all
F	>82	>82	>1.66	0.95–0.68	Shuffling

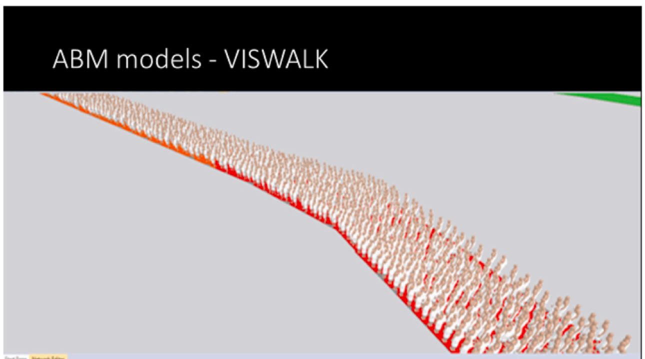

Fig. 4.1. Screenshot of the pilgrims moving in the ABM.

Most crowding models adopt a level of service classification (LOS) to help contextualise crowd density (i.e. to distinguish between different density levels and their impact on the affected individuals). Fruin's (1971) LOS has been used as a benchmark in many studies (Basbas et al., 2020) and has been configured and developed within VISWALK. The Fruin classification is shown in Table 4.1. 'A' represents the situation of unimpeded free flow and 'E' and 'F' are the critical densities that will cause congestion. This variation is based on factors such as average personal space and speed of travel.

The simulation time for our model is around 60 minutes (3600 seconds) which is roughly the time it takes pilgrims to walk from the farthest point of Mina (near to Muzdalifah) to Jamarat Bridge. Also, the average speed for elderly people is set at 1.16 m/s and 1.38 m/s for the rest (cf. Chandra and Bharti, 2013). As the maximum number of individuals that can be simulated by the available PTV VISSIM (2021) licence is 100,000, we begin with 10,000 agents moving at once and

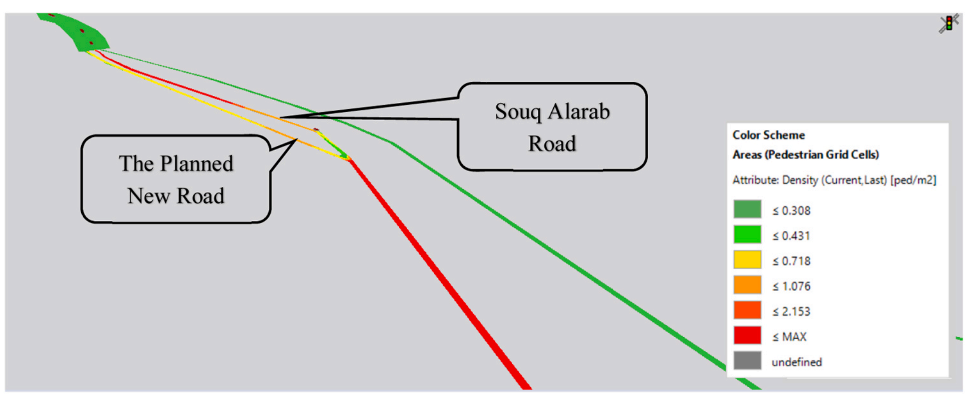

Fig. 4.2. The top view of Souq Alarab road and the planned new road.

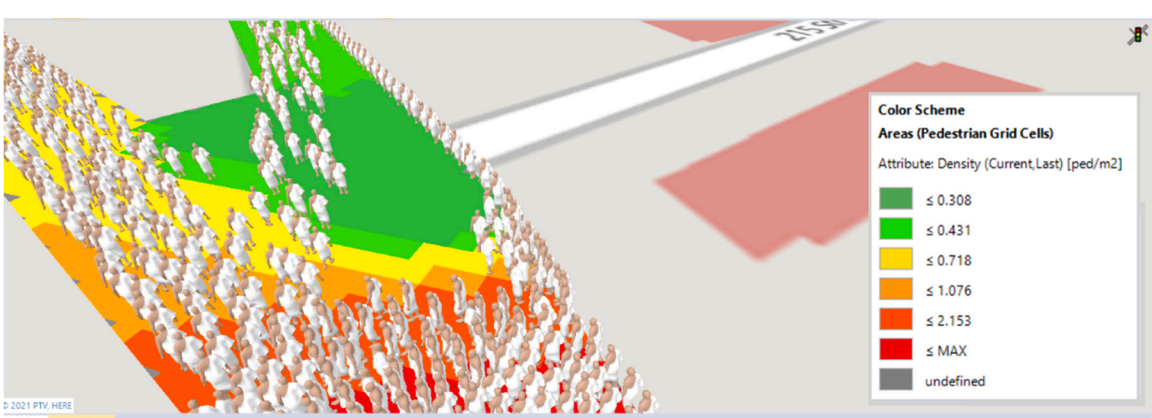

Fig. 4.3. Agents choose between routes at the new junction.

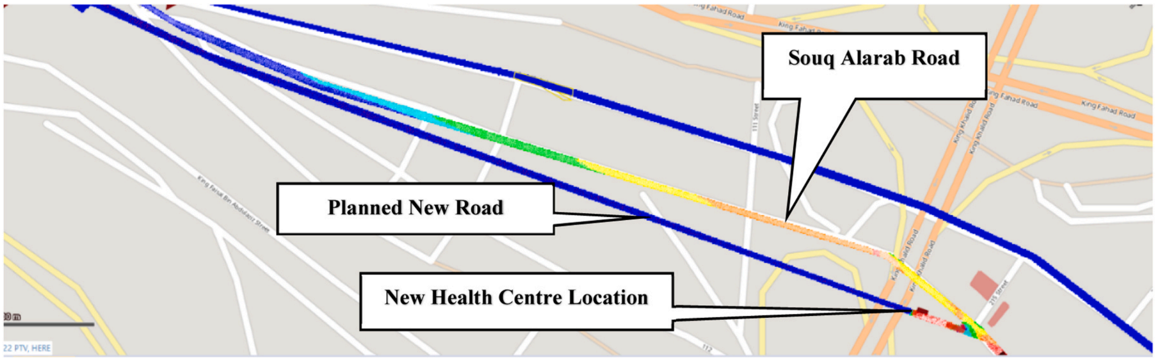

Fig. 4.4. Health centre located along the new route.

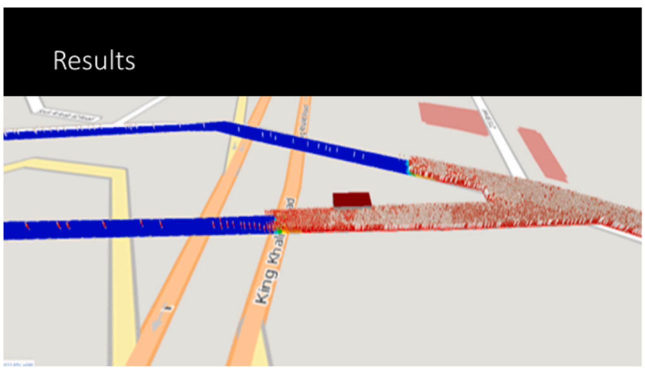

Fig. 4.5. Congestion around the health centre.

then explore the volumes (numbers of agents) that would trigger concerns of danger.

As Fig. 3.6 showed there are a number of pinch points where congestion is greatest. One of these is along Souq Alarab road. Thus we now show the results of the ABM along this road segment. Fig. 4.1 shows a screenshot of the pilgrims moving through the network using VISWALK.

For 10,000–50,000 pilgrims the model shows no sign of congestion. However, between a more realistic 75,000–100,000 pilgrims, levels of congestion begin to build up. At the 100,000 level we estimate a Fruin score of 'E' which represents 'restricted movement'. This is a major warning sign – if we could simulate more agents, then we would quickly reach a grave situation. There are several possible policy responses. One is to stop pilgrims from joining the road at earlier junctions whilst congestion eases. This might be difficult to police (which was the case when staggered start times from the tented city was introduced in the past) and may also mean people waiting in the heat of the day. A second would be to build a relief road at the highest point of congestion. To test this scenario we suggest the building of a new relief (by pass) road adjacent to Souq Alarab Road. Fig. 4.2 shows the location of the new road (note, other bottlenecks could easily be examined in a similar fashion).

This new road allows pilgrims to take an alternative route. Fig. 4.3 shows the agents approaching the junction and the less congested segments after the road splits.

The new road helps congestion – now the 100,000 is divided equally amongst the routes (and the Fruin scores return to category C – slower speed). However, the location of health centres is also problematic. The location-allocation model is keen to locate a centre around this junction area (see Fig. 4.4). Most existing health centres in Mina are built as close to the road as possible for pilgrims to receive medical attention quickly. However, we argue that if they are too close to the road it causes additional problems – people queuing on the road itself causing additional blockages.

Fig. 4.5 shows the pilgrims queueing next to the entrance on the left hand side of the health centre as we assume 10 % may wish to stop, take in water and generally seek treatment for heat exhaustion etc. (we can easily see the impacts of more pilgrims stopping).

Next, we can use the ABM to help plan a better location for the health centre. If we can build the centre 100–200 m away from the road we can observe greater potential to allow pilgrims to queue in a safer

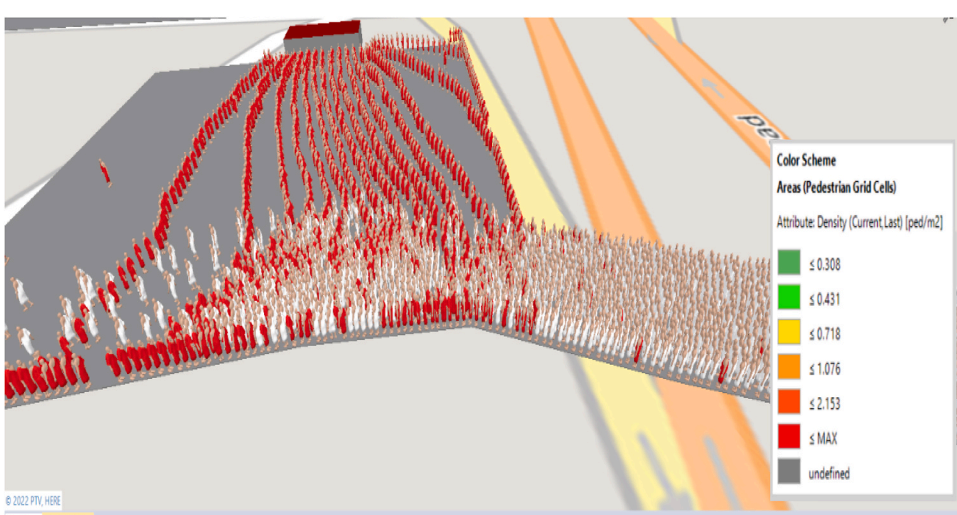

Fig. 4.6. Shifting the service location from ' Souq Alarab' road.

environment. Given the number wanting to attend the health centre, and the space they now have, the software shows how 15 lines can be set up (deemed to be optimal in this case following many different scenarios tried) to allow the pilgrims to queue more safely (see Fig. 4.6). Hence, we suggest that decision makers should plan for sufficient space specifically for waiting to allow a freer passage for those pilgrims walking on towards Jamarat. Further, this experiment confirms the importance of using an ABM in a specific scenario in terms of mitigating the crowd around that area and facilitating the flow towards Jamarat.

5. Conclusions

We conclude this paper by examining the policy implications of the work presented. Service provision is a very important issue for decision makers especially for an international event such as the Hajj. For a few weeks of the year the eyes of the world are on the Saudi authorities and any major incidents are reported globally. Health centres have been chosen in this paper because of their importance in ensuring the safety and well-being of the many millions of visitors. Planning services is always a compromise between efficiency (good use of scare resources) and effectiveness (the ability to operate these services with a degree of equity in access). The results of the LAM show that it is possible to distribute services more efficiently and effectively, certainly in comparison to the actual current distribution of facilities. We have shown how solutions can be obtained which allow far more pilgrims a service coverage within 300 m of their night-time locations and also, through the peak analysis of demand movements, through the daytime as well. This has been shown to be the case even when we reduce the number of service locations across the Hajj (potential cost-cutting exercises). With a reduced set of facilities it is still possible to improve the accessibility of pilgrims compared to the present set of facility locations.

The study of different number of pilgrims moving throughout the road network using the GIS network analysis and the ABMs gives us greater insight into what the congestion levels across Mina network might be at different times of the day. The ABMs allow us to see when problems might appear and take steps to alleviate these. The ABM analysis has been useful to look at flows, especially around potential bottlenecks. The addition of a new road alongside 'Souq Alarab road' would help mitigate congestion at a key bottleneck area. Although expensive in the short term, the long term benefits of reduced injuries and deaths would be considerable. Another policy outcome is the suggestion that the relocation of health centres away from adjacent areas on the road network should be considered. The ABMs have also shown clearly how moving the health centres away from the main roads eases local congestion hot spots.

Despite the potential greater costs with new facilities and new roads, the results of our analysis may have some positive implications for costs. Although the Saudi Government earns a substantial income from the Hajj (most importantly through taxation of accommodation) it also bears the costs of service provision. For example, health care is provided free of charge at the point of usage during the event. The results of the LAM could help revamp staffing rotas – not only can the model provide optimal locations they can estimate the workloads associated with each facility location (based on the volume of local demand), meaning the thousands of health workers could be also located more optimally. The results of the modelling over time would be especially useful here: for example, staff could be transferred during the day from the Muzdalifah or Arafat tented city areas to support the greater demand expected to be on routes to the Jamarat Bridge.

This study shows the potential of combining LAM and ABM to help service planning in a major temporary city which includes a substantial amount of pedestrian movement. If our policy recommendations could be taken on board we believe we would leave a legacy of improved health and safety at future Hajj (or similar) meetings.

CRediT authorship contribution statement

Malleson Nick: Writing – review & editing, Writing – original draft, Supervision, Methodology, Formal analysis, Conceptualization. **Alotaibi Muteb:** Writing – original draft, Software, Investigation, Formal analysis, Data curation. **Clarke Graham:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Muteb Alotaibi reports financial support was provided by Royal Embassy of Saudi Arabia Cultural Bureau in London. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors are grateful for comments received from discussants and participants at a presentation of this paper at the North American Regional Science Association meeting inSan Diego, November 2023. Particular thanks go to main discussants Chris Blake and Catherine Kreutzen of Emory University. We would also like to thank Holy Makkah Municipality -Royal Commission for Makkah city and holy sites-Ministry of Hajj and the PTV Group for their cooperation and support.

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