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DISEASE SPREAD SIMULATION TO ASSESS THE RISK OF EPIDEMICS DURING THE GLOBAL MASS GATHERING OF HAJJ PILGRIMAGE

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ABSTRACT

Global mass gatherings can pose a risk for communicable disease outbreaks. In these events, millions of people gather at a specific location over a specific period of time from different regions of the world. Such settings have the potential to import and/or export infectious diseases to and from the host countries by international participants. Planning and preparing for public health risks at global mass gatherings is a challenging and complex process. Advanced risk assessment tools are important to identify potential disease outbreaks. In this study, we propose a computational epidemic simulation framework to simulate disease transmission from the arrival, to the departure of international participants in the global event of Hajj. Computational simulations of disease spread in global mass gatherings provide public health authorities with powerful tools to assess the implications of these events and to evaluate the efficacy of prevention and control strategies to reduce their potential impacts.

1 INTRODUCTION

Global Mass gatherings (MGs), such as major sports events, religious pilgrimages, and music festivals, attract crowds from different parts of the world. At these events, attendees are at high risk of serious public health threats (Ahmed and Memish 2018). The international travel associated with global gatherings can rapidly spread infectious diseases across the world and lead to public health emergencies on a global scale. The nature of these global events results in diverse demographic characteristics, susceptibility levels, and disease exposure histories among the spectators and participants. Close contacts between attendees in confined and crowded spaces throughout various stages of these events facilitate the transmission of infectious diseases. Disease outbreaks have been reported in several mass gatherings of varying sizes with the most commonly reported infections being respiratory viruses including different strains of influenza (Hoang and Gautret 2018; Tabatabaei and Metanat 2015). The implementation of various public health measures, such as event cancellation, screening at entry points, and vaccination requirements, may successfully prevent and control the spread of diseases among attendees at global events (World Health Organization 2015).

Mass gatherings present a challenging setting for monitoring infectious diseases due to their large scale and dynamic nature. These challenges necessitate the use of advanced computational tools during the planning and organizing process of global events for disease outbreak prediction and detection. Computational modeling and simulation of disease transmission can be utilized in mass gatherings to simulate the contact and mobility patterns of the participating populations and model the spread of epidemics at these events. There have been few studies that either discuss the various aspects of epidemic modeling in global MGs in general (Chowell, Nishiura, and Viboud 2012) or propose computational epidemic models targeting small-scale or local MGs (Shi et al. 2010; Stehlé et al. 2011).

This paper presents a computational epidemic simulation framework to assess the risk of disease outbreaks at the global event of Hajj, the Muslim pilgrimage to Makkah. Every year, approximately three million pilgrims arrive from over 186 countries to perform the Hajj at the holy sites in Makkah. The event of Hajj is characterized by limited geographical space and a short period of six days. Pilgrims in such an overcrowded and diverse gathering face serious risks of contracting communicable diseases (Rahman et al. 2017). The increasing number of pilgrims every year amplifies the risk of these various health threats to both the visiting pilgrims and potential contacts in their home countries. The vast majority of international pilgrims attending Hajj arrive from low-income countries with sub-standard or limited health care and disease surveillance systems, posing further challenges to public health authorities in Saudi Arabia to ensure the safety of all pilgrims. We use the proposed framework to simulate the outbreak of H1N1 at Hajj as a case study to demonstrate the simulation and analysis of various disease transmission scenarios throughout the stages of a global mass gathering from arrival to departure of participants in this study. The results are shown as a proof of concept and the framework can be used to simulate any close-contact disease in other mass gatherings.

In the next section, we provide a detailed description of the main components of the epidemic simulation framework. Section 3 explains the experimental setting and presents the results of the epidemic simulations during the main stages of the global event of Hajj. Finally, Section 4 concludes this paper with a summary of the main findings of the presented study.

2 METHODS

The computational epidemic simulation framework (Figure 1) consists of a population model that generates a synthetic population of international participants based on data collected from previous Hajj seasons, a travel model to assign the arrival and departure patterns to the participants, an event model to manage stage settings, a contact model to generate contact rates and social mixing for each stage of the event, and finally an epidemic model to classify and track the transmission of the disease among the participants.

2.1 Travel Model

The majority of international participants in global mass gatherings arrive by air. In the event of Hajj, 92-94% of foreign pilgrims arrive by air via two main entry points, the Jeddah and Madinah international airports. The air-travel data of five Hajj seasons (2010-2014) is obtained from the Saudi General Authority of Civil Aviation (GACA). While the actual Hajj rituals last for 6 days, international pilgrims may arrive 30-35 days before the starting date of the Hajj and may stay for 30-35 days after the completion of the Hajj. The arrival process starts slowly with a few flights (6-14 flights per day) at the beginning and increases steadily until it reaches its peak during the last week of the arrival period with about 90-150 flights per day.

Unlike arrival rates, departure rates of the five Hajj seasons start with the highest rate in the first week of the departure period and decrease with time reaching the minimum rate on the last day of the departure period. Based on the collected data, the rates of arrival and departure of the international pilgrims are not expected to change significantly in future Hajj seasons as the majority of foreign pilgrims arrive from low-income countries. Most international pilgrims cannot afford the cost of accommodation to stay at the holy sites for a long time before or after the actual rites of Hajj.

For simulating the arrival and departure of Hajj pilgrims in Saudi Arabia realistically, the arrival and departure rates during previous Hajj seasons were analyzed. Based on this analysis, the arrival and departure periods were divided into several time intervals with different rates. The model generates daily flight arrival/departure data using a compound non-homogeneous Poisson process with fixed batch sizes for these time intervals. Rates of arrival and departure were obtained by averaging the number of flights

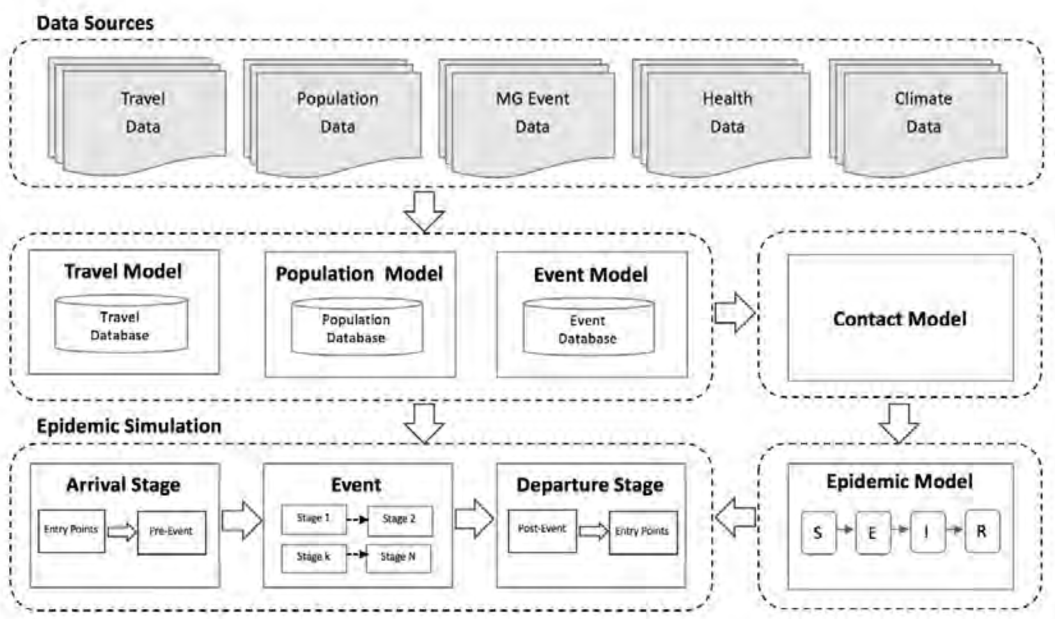

Figure 1: An overview of the computational epidemic simulation framework proposed to simulate disease outbreaks at global mass gatherings.

per time interval for five Hajj seasons (2010-2014). Each flight is assigned several features, including the flight number, origin/destination, arrival/departure date and time, and the number of passengers.

2.2 Population Model

The population model is used to generate a synthetic population for international pilgrims. Since the focus of this study is to simulate pilgrims and their interactions throughout the different stages of Hajj, sub-populations other than pilgrims, such as official workers and local residents of Makkah and Madinah, are not represented in this synthetic population. The number of international pilgrims is determined based on travel data generated by the travel model.

The population model creates pilgrim objects/agents based on the travel data. Each pilgrim has a unique identifier that can be used to assign, track, and update the movements and health status of that pilgrim. While the country of origin is assigned based on flight arrival data, the other demographic features, including, age and gender are attributed based on available statistics from related sources. To assign gender to each pilgrim, a random sample is generated using the binomial distribution. The population of pilgrims is divided into six age groups and each pilgrim is randomly allotted to one of these age groups maintaining the overall distribution of pilgrims by age. These attributes play a crucial role in determining social mixing and contact patterns during Hajj, and are be used by the event and contact model.

2.3 Event Model

All global mass gatherings start with the arrival stage, the actual event, and when the event is concluded all international participants depart back to their home countries. At these gatherings, participants may follow specific rituals or may attend/perform activities based on personal preferences. While data about travel patterns associated with the event is used and integrated by the travel model, data related to the setting and venues of the event is used by the event model to extract the main parameters to simulate each stage.

Depending on the current activity or stage, all participants or groups of participants are assigned to a specific location. Each location type represents a distinct environment for the simulation of the contagion process. Size and features of the expected population, the capacity of the location, the duration participants spend at that location, potential social mixing, and possible activities that will take place at a specific location direct the simulation of the disease spread at a particular location during a specific stage of the event. The event model maintains a location class with a list of generic features such as capacity, size, population density, and the number of units. This generic class can be extended to generate sub-classes of different locations based on the mass gathering under study. This model forms the core of the disease simulation framework at a global mass gathering as attributes like population density and capacity play a key role in determining the number and duration of contacts between individuals which in turn governs the transmission of disease.

2.4 Epidemic Model

The stochastic SEIR (Susceptible-Exposed-Infected-Recovered) model (Britton 2010) is used to assign a disease status (susceptible, exposed, infectious, or recovered) to each individual based on the progression of the infection over time. The transition of individuals between these groups reflects the propagation of the disease in the population. After being in contact with an infectious individual, a susceptible individual may move to the exposed compartment, indicating that an individual is infected but not yet infectious. Individuals move from the exposed compartment to the infectious compartment at the end of the latent period and can transmit the disease to other susceptibles. An infectious individual recovers from the disease after the infectious period and may gain immunity to the disease.

The infectious period starts with an individual being asymptomatic. It is important to include the asymptomatic infectious disease status to simulate the transmission of the disease in global mass gatherings. Asymptomatic individuals cannot be detected during screening of symptoms at entry points which means they can join other participants and transmit the disease. Furthermore, since asymptomatic individuals do not show any symptoms, fewer preventative measures or behaviors will be taken either by them or other susceptible individuals near them. However, due to a lack of clear and consistent transition rate from the onset of infectiousness to the onset of symptoms for the H1N1 infection, the asymptomatic state is not included in all conducted simulations of disease spread at the different stages of Hajj. Given reliable data, however, the framework can be extended to take into account the asymptomatic infectious state.

2.5 Contact Model

The transmission of an infectious disease is influenced by the number of contacts per individual per unit of time and the mixing patterns for individuals in a population. Most existing studies have explored rates and patterns of contacts in various confined settings such as households, schools, and workplaces. However, there is a lack of information about the number of contacts and the social mixing in large or open settings with high population densities such as airport terminals and mass gatherings. Contact rates in a location setting are dependent on the population density at the location, hence instead of using a constant contact rate for the entire simulation, we employ the spatial kernel density function described in (Hu, Nigmatulina, and Eckhoff 2013) to approximate the number of contacts per day for each pilgrim at each stage of the Hajj. Equation 1 estimates the contact rate relevant for disease transmission where r is the maximum infectious radius of the disease being modeled. In respiratory diseases such as Influenza, the infectious diameter is determined by how far disease droplets travel in the air when an infected person sneezes, coughs, talks, or breathes. For influenza the value of r has been shown to be 6 feet (Fiore et al. 2011). ρ_0 is the maximum population density in that location, and ρ is the average population density. c is the fraction of contacts each individual has among the calculated effected population. In this model, the contact rate decreases with distance, and shows an initial growth with an increase in density, but saturates for higher values of ρ which represents realistic contact behavior between individuals.

$$C = c\pi\rho_0(1 - e^{-r^2\frac{\rho}{\rho_0}}) \tag{1}$$

The variations in contact patterns at global mass gatherings arise from event type and venue, population density, participants demographics, and cultural differences. The contact patterns and the movements of the pilgrims are influenced by their characteristics. For instance, international pilgrims arrive from the same country or speak the same language have a higher likelihood to interact with each other for a longer period of time. Upon their arrival, international pilgrims are clustered into six establishments based on their countries. These clusters of pilgrims may mix together in various locations while staying at Makkah or Madinah prior to Hajj, during the rituals, and after completing Hajj and waiting for departure.

2.6 Agent-Based Simulation

Agent-based modeling can be used to simulate disease transmission at an individual level providing a realistic representation of epidemic progress among individuals. Agent-based models have been widely used in epidemic simulations in the past. For example, Carley et al. (Carley et al. 2006) proposed a BioWar simulation tool that combines several computational models such as a multi-agent model, a spatial model, social networks, and a disease model into a single integrated system that simulates the impact of a bioterrorism attack on a city using census, school district demographics, and other publicly available data. In another small scale study, Patlolla et al. (Patlolla et al. 2004) developed a computational model to analyze tuberculosis outbreaks in a homeless shelter using an agent-based modeling tool (StarLogo).

In this study, agent-based modeling is used to simulate the disease progression and interactions between pilgrims at the main stages of Hajj. Figure 2 illustrates the sequence and duration of the stages of Hajj. Every agent represents a pilgrim or a group of pilgrims. A pilgrim agent maintains demographic, health, arrival, and event-related attributes. Depending on the simulation settings, an agent may follow preventative behaviors such as wearing a mask, sanitation or distancing from symptomatic individuals. A location parameter is assigned to each agent to track the current location of the agent and it can be determined on the basis of the current stage or ritual, or based on a likelihood of remaining at a specific location or move to a different location(s). Managing millions of agents at all the stages is both memory and time prohibitive, therefore the pilgrim agents are aggregated by country, gender or other demographic features to form sub-population agents for stages in which it is known that contacts between pilgrim agents from two groups are impossible or highly unlikely.

Each pilgrim can interact with other pilgrims while respecting the time and space constraints of the stage or ritual being simulated. In every simulation, interaction patterns will be guided using the contact model and the contagion process is simulated according to the epidemic model. If an infected agent interacts with a susceptible agent, there is a possibility of disease transmission. Throughout the different simulations, instances of infection transmission are recorded and corresponding parameters of the affected agents are updated. Each simulation loads pilgrims from the population database to simulate their interactions and to run the epidemic model. Updates of the epidemic-related fields associated with each pilgrim are uploaded to the population database.

In every agent-based simulation, a specific stage of the Hajj is captured, and the disease spread across pilgrims is simulated. Each simulation is controlled by specific parameters according to a stage or ritual being simulated. The outcome of the simulation during a stage is used in the simulation of the subsequent stage(s). The size of the time step of a simulation is selected according to the estimated time of each stage and the duration of the entire event. Depending on the mass gathering individuals may participate for several days or a few hours per day. Hence, the simulation may have an hourly or daily step size.

3 DISEASE SPREAD SIMULATIONS AND RESULTS

There are several factors that can affect the spread of communicable diseases at a global event, including, environmental and hygienic conditions at the host nation, timing and season of the event, duration of the event, global outbreaks, the density of participants and their origins. In general, global mass gatherings are characterized by conditions that contribute to the transmission of close-contact infections, including

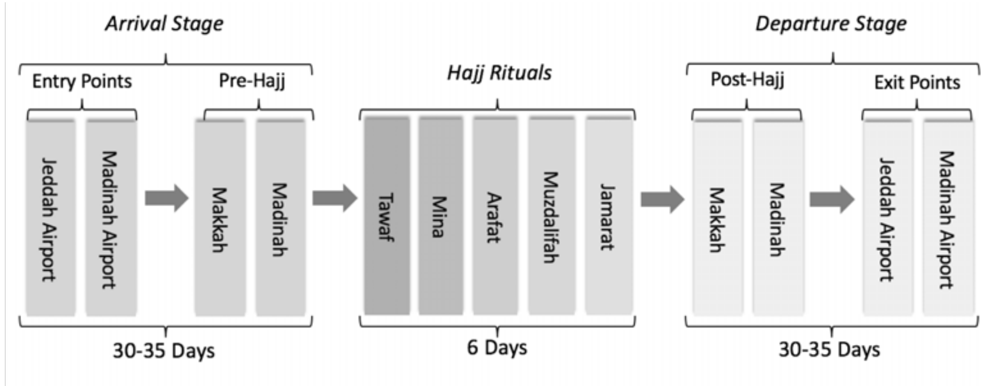

Figure 2: Illustration of the sequence and duration of the main stages of the Hajj.

several types of influenza. In this study, the epidemiology of influenza A H1N1 virus (Table 1) is used to parameterize the epidemic model.

Table 1: Disease spread parameters used to simulate H1N1 outbreak.

Parameter	Value	Reference
Mean Latent Period	2.7 days (standard error of 0.214)	(Jhung et al. 2011)
Mean Infectious Period	3.38 days (standard error of 0.673)	(Tuite et al. 2010)
Infectious Radius	6 feet	(Fiore et al. 2011)
Basic Reproduction Number, R_0	$1.3-2.4$	(Boëlle et al. 2011; Fraser et al. 2009) (Tuite et al. 2010)

The international pilgrims were seeded with 0.2% infectious individuals from the total arriving pilgrims at Jeddah and Madinah airports over the entire arrival period at each airport starting from the first day of arrival. The number of infected individuals in a flight were calculated using a binomial probability distribution. Due to the uncertainty in epidemic models and their stochastic nature, Monte Carlo simulation of 100 realizations of each disease transmission scenario is used to capture the effect of randomness in disease transmission and interactions among participants. The final results of each disease spread simulation are summarized by averaging (arithmetic mean) the total number of individuals per each health status along with the confidence interval range ($\alpha = 0.05$) across the 100 simulation runs.

3.1 Baseline Results

3.1.1 Arrival Stage

Simulating the movement and mixing patterns of international pilgrims during the arrival stage is divided into two phases: 1) Entry points phase and 2) Pre-Hajj phase. International pilgrims arriving at Jeddah airport must depart to Makkah and pilgrims entering the country via Madinah airport may stay in the holy city of Madinah for several days (up to 30-35 days), then travel to Makkah before the starting day of the Hajj rituals. The exclusive Hajj terminals at each airport restrict the movement of pilgrims within a limited area and exclude them from mixing with other incoming passengers. International pilgrims arrive in the same flight or within the same time slot often stay in confined spaces to complete the airport procedures. The contact rate and social mixing at this phase are influenced by the daily arrival rate of incoming flights and their origins.

The average time to complete these procedures at the two main airports ranges from 2 to 4 hours per flight. Since the duration of the epidemic simulation at the airport phase is shorter than the infectious and latent periods of the disease, there will be no changes in the infectious status or timer of the initially infected pilgrims. As shown in Figure 3, the only change that can be seen after executing the epidemic simulation at both inside and outside airport phases is in the number of exposed pilgrims or new cases. At the end of the 35 days of arrival, 0.04% of the arriving pilgrims get infected at each airport.

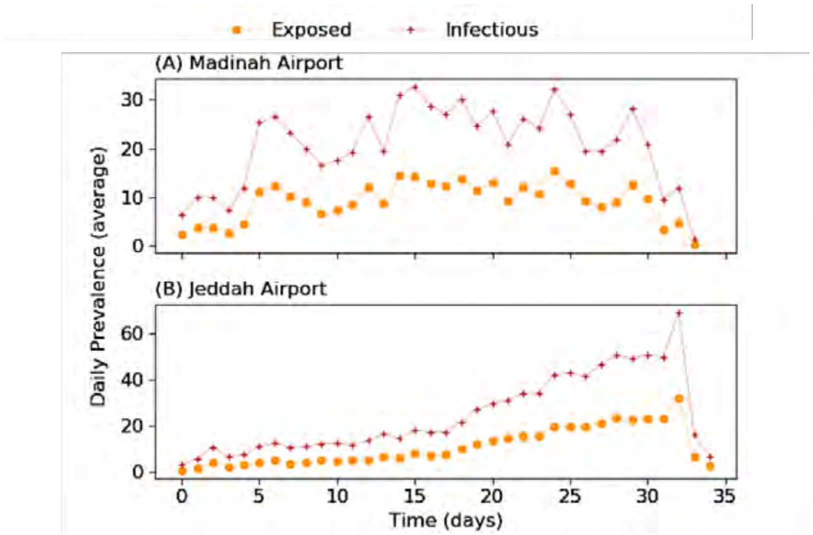

Figure 3: Daily results of disease spread simulation among arriving pilgrims during the airport phase.

While the mobility patterns of pilgrims at the entry points are restricted to particular areas within a limited time frame, no restrictions are applied on their movements during the entire period they spend at Makkah or Madinah in the pre-Hajj phase. In both cities, pilgrims move back and forth between their lodgings, grand mosque, and common areas such as shopping centers and public transportation. However, there is insufficient information about pilgrims'movements or accommodation arrangements during this phase. Hence, agent-based simulation of the pre-Hajj phase captures and simulates the interactions and disease spread among pilgrims at five distinct time slots per day reflecting the five prayers at the grand mosque in each city.

The number of pilgrims in Madinah each day is the difference between the daily arrivals from the airport and daily departures to Makkah. While there is a fluctuation in the population size in Madinah, the total number of pilgrims in Makkah increases on a daily basis by the international pilgrims arriving from Jeddah airport and pilgrims coming from Madinah during the pre-Hajj phase. Figure 4-(A) illustrates the disease outbreak curves in terms of the average number of exposed, infectious, and recovered pilgrims who are currently in Madinah. The results of disease spread simulation in Makkah during the pre-Hajj phase are shown in Figure 4-(B). Because of a low average departure rate from Madinah city to Makkah, the proportion of pilgrims arriving in Makkah from Madinah shows a minor impact on the prevalence and the total rate of infectious and exposed. At the end of the pre-Hajj phase in Makkah, 2.6% of the total $912,390$ arriving pilgrims contracted the disease and they are either exposed (0.4%), infectious (0.5%), or recovered (1.7%).

3.1.2 Hajj Rituals

Upon their arrival, international pilgrims are classified into six establishments based on their country of origin. In all Hajj rituals, international pilgrims must follow a timetable to complete the rituals according to their establishment. From the first day of Hajj, all pilgrims must move to their accommodation at the Mina campus where they stay during the Hajj. Table 2 lists the duration, frequency, social mixing, and the location for each ritual of Hajj.

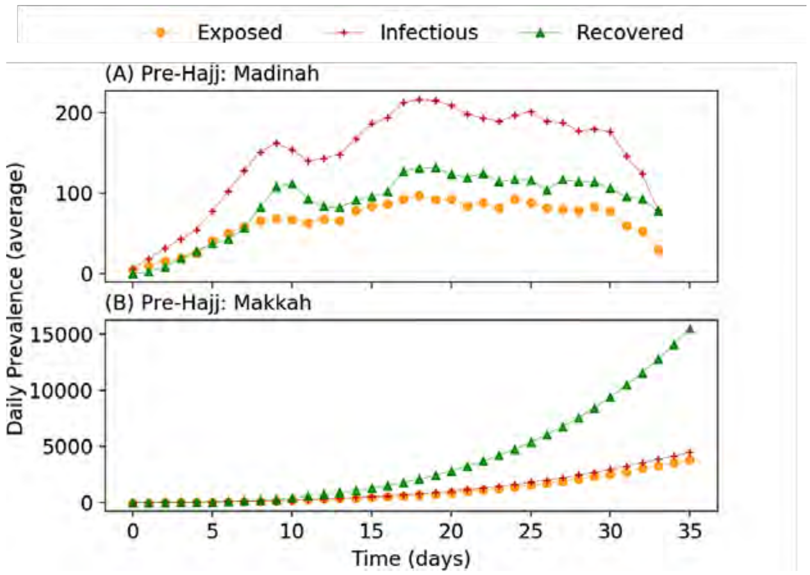

Figure 4: Disease transmission results among international pilgrims during the pre-Hajj phase at Makkah and Madinah.

In the agent-based model, relevant features of each agent can be used to aggregate several numbers of agents into a higher level to represent an entire establishment. For instance, the disease simulation among pilgrims at their accommodations in Mina requires further grouping of male and female pilgrims due to gender segregation at the campus of Mina. The implementation of the agent-based model allows the creation of sub-populations of female and male pilgrims who belong to the same establishment. The contacts between pilgrims are assumed to be homogeneous with a higher contact rate for intra-establishment contacts and a lower contact rate for inter-establishment contacts. By the end of the last Hajj ritual (Farewell Tawaf), 9% of the total international pilgrims contracted the disease and they were exposed (2%), infectious (3%), or recovered (4%).

Table 2: The main parameters used to guide the disease spread simulation at each ritual of Hajj.

Ritual	Location	Duration	Social Mixing
Staying at Mina	Mina campus	6-12 hours per day	Establishment-level with gender segregation
Staying at Arafat	Arafat plain	12 hours	Establishment-level with gender segregation
Staying at Muzdalifah	Muzdalifah plain	12 hours	Individual-level
Stoning	Jamarat bridge	6-12 hours per day	Establishment-level
Tawaf	Grand mosque in Makkah	3-6 hours	Establishment-level

3.1.3 Departure Stage

The international pilgrims are divided based on departure airports into two subpopulations. Pilgrims who are departing from Jeddah airport are assumed to spend the post-Hajj phase at Makkah and international pilgrims who arrived from Madinah airport are assumed to go back to the holy city of Madinah and stay at Madinah until their departure back to their home countries from Madinah airport. Similar to the pre-Hajj phase at each city, the disease spread simulation is conducted at the grand mosque during five-time slots reflecting the daily five prayers. The epidemic results of the last Hajj ritual, Farewell Tawaf, are used to simulate the disease spread among pilgrims during the post-Hajj phase at Makkah and Madinah.

Figure 5 shows the number of individuals in the four disease compartments after the execution of the simulation during the post-Hajj phase in Makkah and Madinah. The average of the daily prevalence over 100 simulation runs is plotted in each curve in the figure. The reported numbers at the end of each simulation run reflect the numbers of pilgrims in each disease compartment after updating disease timers and changing disease status of infected pilgrims accordingly. Unlike the pre-Hajj phase at the arrival stage, the number of infectious individuals decreases over time as pilgrims are departing from Makkah and Madinah.

Table 3: Simulation Results: Breakdown of the health status of the pilgrim population on the last day or time each ritual of Hajj is completed.

Ritual	Susceptible	Exposed	Infectious	Recovered
Mina	840,623 (92%)	9,441 (1%)	25,475 (3%)	36,851 (4%)
Arafat	880,221 (97%)	10,446 (1%)	4,769 (0.5%)	16,954 (2%)
Muzdalifah	875,870 (96%)	9,170 (1%)	8,833 (1%)	18,516 (2%)
Stoning	845,893 (93%)	14418 (1.5%)	23,157 (2.5%)	28,923 (3%)
Second Tawaf	87,1414 (95.5%)	13,627 (1.5%)	8,833 (1%)	18516 (2%)
Farewell Tawaf	831,485 (91%)	18,579 (2%)	25,475 (3%)	36851 (4%)

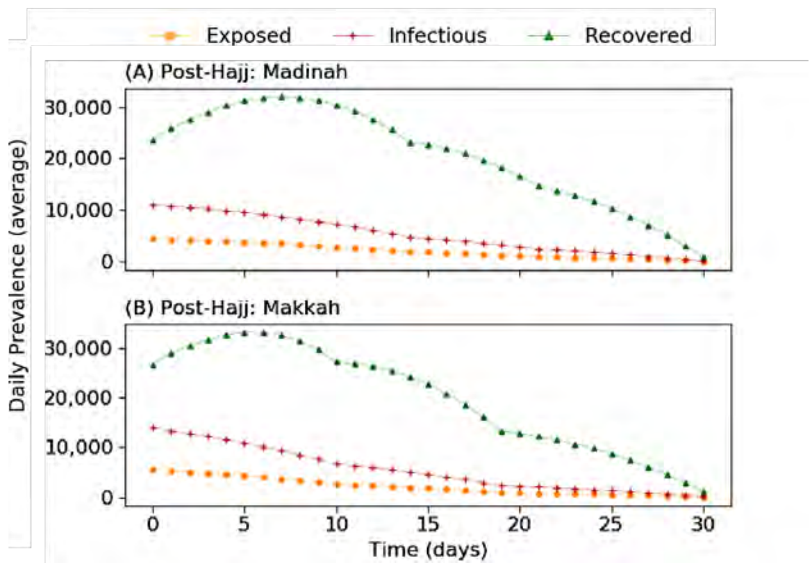

Figure 5: Disease transmission results among pilgrims during the post-Hajj phase at Makkah ad Madinah.

The duration of epidemic simulation at the airport phase is estimated to be in the range of two hours based on departure data. The daily changes in the number of new cases or exposed pilgrims after executing epidemic simulation at each airport are shown in Figure 6. The pattern of the number of infected pilgrims in Figure 6 reflects the departure rates of international pilgrims at each airport. Based on the collected data of the daily number of Hajj exclusive flights departing from Jeddah and Madinah airports, the departure rate starts slowly with few flights on the first days. Then for the next two weeks, the departure rate reaches a daily average of 100 flights from Jeddah airport and 70 flights from Madinah airports.

To study the impact of contact rate and patterns on the progression of the disease, a simulation of the disease spread at the pre-Hajj phase is executed assuming a homogeneous mixing with a constant contact rate. By the end of the 35 days of arrival during the pre-Hajj phase, 95% of international pilgrims contracted the disease compared to 2.6% using our epidemic simulation framework.

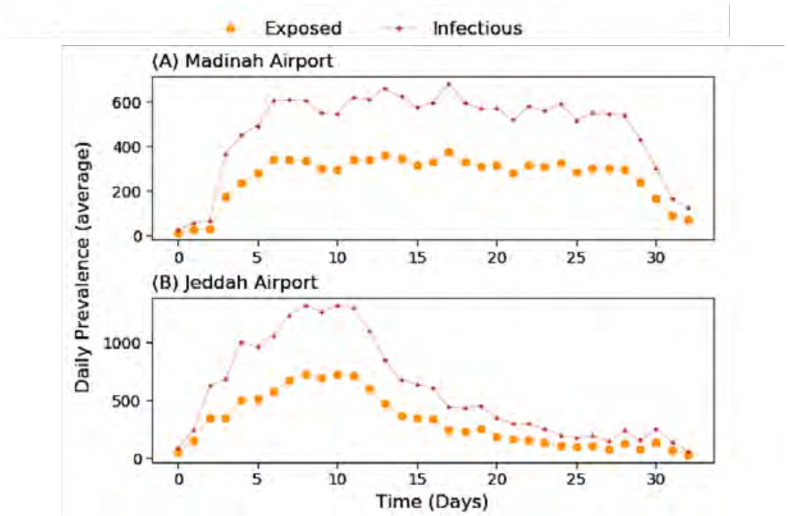

Figure 6: The daily number of new cases among pilgrims departing back to their home countries at airport phase over the departure period of 30 days.

3.2 Preventative Measures Results

Various intervention procedures can be implemented in global mass gatherings by host countries upon the arrival of international participants such as vaccination requirements and screening at entry points. In addition to these measures, public health authorities in host countries and home countries of participants publish recommendations for attendees to maintain healthy and precautionary behaviors such as wearing a face mask, personal hygiene, and social distancing. The agent-based epidemic framework proposed in this study includes parameters to assign vaccination status and preventative actions for each individual. The vaccination coverage, the proportion of participants following a preventative behavior, and the effectiveness of each measure are input parameters for the framework and can be modified depending on the data. In the framework, the effect of each preventative measure is simulated by reducing the transmission probability by the effectiveness or efficiency of the applied measure.

To study the effectiveness of vaccination at the arrival stage of Hajj, we assume H1N1 vaccines administered at least 4 weeks prior to the arrival at Hajj. The effectiveness of H1N1 vaccine is assumed to be 75% (Khazeni et al. 2009). Since keeping social distance is not a practical action during most of the stages in Hajj due to high population density, another preventative measure that can be explored when simulating disease spread at Hajj is wearing a face mask. While there are different types of face masks, such as surgical, N95, and N99 respirators masks, we assumed that pilgrims only have access to the surgical mask. If an infectious individual is wearing a surgical face mask, the value of effectiveness is set to 5%, and if a susceptible individual is wearing a surgical face mask, then effectiveness will be set to 2% (Tracht, Del Valle, and Hyman 2010).

Disease spread simulations are conducted at the pre-Hajj phase in both cities of Makkah and Madinah using different coverage rates of 10%, 15% and 25% from the whole population of pilgrims for each measure. In these simulations, pilgrims following the prevention measures are chosen randomly. While the cumulative number of cases at the end of the 35-days of arrival showed that the higher rate of vaccination can be an effective measure to control the disease spread and reduce the number of cases by 50%, the simulation results of wearing face masks are insignificant compared to baseline epidemic results.

4 CONCLUSION

The data-driven computational framework developed in this study effectively simulates the contagion process at the global religious gathering of Hajj from the arrival to the departure of the international participants. The implementation of the agent-based model to simulate the disease spread among international participants at the global event of Hajj provides a flexible aggregation of pilgrims at multiple levels according to the setting and requirement of each Hajj ritual or phase. The results obtained from the epidemic simulations in this framework show a substantial impact of the demographic and mobility patterns of the heterogeneous population of pilgrims on the progression of the disease spread in the different stages of Hajj. Additionally, these simulations suggest that the differences in the spatial and temporal settings in each stage significantly affect the dynamic of the contagion process. Finally, the epidemic simulations conducted at the different stages in this study illustrate the impact of the differences between the duration of each stage in the event and the length of the infectious and latent periods.

In pre-planned global events, it may not be possible to cancel, postpone or impose travel bans for the event in spite of potential health threats or ongoing disease outbreaks. Specifically, for religious pilgrimages like Hajj, it is impossible for the host nation to cancel the event or ban pilgrims from affected regions from participating. Therefore, the integration of computational tools with detailed data from official sources will allow public health authorities to estimate potential epidemics at each stage or day of the event and to evaluate the efficiency of control strategies to reduce their impacts. This study contributes to a better understanding of epidemic modeling in the context of global mass gatherings to predict the risk of disease pandemics caused by associated international travel.

This study demonstrates the feasibility of developing efficient computational simulations to track infectious diseases in global mass gatherings. The methodology of simulating disease spread at the main stages of a restricted mass gathering, such as the global event of Hajj, is transferable to other pre-planned global mass gatherings. However, in a more relaxed setting attendees have more independence to decide and time their activities, movements, and contact patterns. The agent-based model used in this study can be developed further to allow agents to make decisions about their movements and interactions with other agents based on a set of rules within the setting of the global event they are attending.

The growing applications of computational modeling and simulation in different areas of public health and the promising results of epidemic simulation and prediction in different settings, emphasize the need to resolve issues related to data sharing and privacy. The availability of required data about global mass gatherings and participants attending these events can result in reliable epidemic forecasting using computational tools. Public health authorities and epidemiologists need to combine their efforts with data scientists to improve disease monitoring in different settings including global mass gatherings.

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