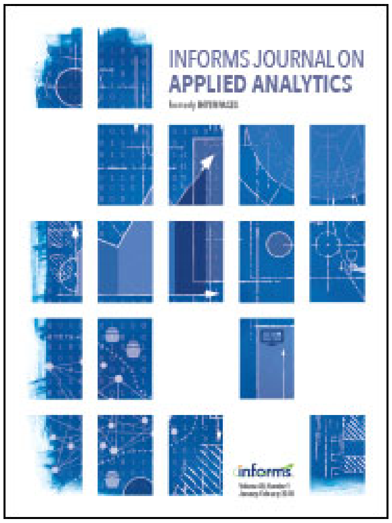

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Improving Pilgrim Safety During the Hajj: An Analytical and Operational Research Approach

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The Hajj, the annual Muslim pilgrimage to Makkah in Saudi Arabia, is one of the largest pedestrian events in the world. Each year, up to four million pilgrims approach the holy sites in the region of Makkah to perform their religious duty. The key ritual, the stoning-of-the-devil, is particularly crowded. Until 2006, several crowd-related disasters led to thousands of casualties. In the aftermath of such a disaster in early 2006, the Ministry of Municipal and Rural Affairs of the Kingdom of Saudi Arabia (MOMRA) launched many projects to prevent future crowd-related accidents. In particular, MOMRA began the development of an operations research (OR)-based decision support system (ORDSS) for crowd management. ORDSS employs a range of tools from OR, analytics, and crowd dynamics. At its core, it implements a scheduling tool and a real-time video tracking system. The video tracking system measures infrastructure utilization, and an integrated series of mixed-integer programs and quadratic programs balance capacity utilization by considering preferred stoning times and infrastructure capacities. The ORDSS provides MOMRA with solutions that enable uncongested and smooth pilgrim flows and extensive real-time reporting. From 2007 to 2014, OR helped stop the tragic loss of human life that resulted from these crowd-related accidents. Unfortunately, a crowd-related disaster, which resulted in hundreds of casualties, occurred during Hajj season 2015; however, for this Hajj season, the authors and MOMRA were no longer in charge of the scheduling and routing recommendations for the stoning-of-the-devil ritual during the Hajj.

Keywords: crowd management; scheduling; decision support system; mass gatherings; Hajj; pedestrian.
History: This paper was refereed.

Each season, the Hajj—the great Muslim pilgrimage to Makkah, Saudi Arabia, one of the largest annual pilgrimages in the world—attracts two to four million pilgrims from all over the world. Until 2006, several crowd-related accidents occurred during the Hajj, resulting in thousands of pilgrim deaths (Table 1). In this paper, we outline how analytics and operations research (OR) techniques helped the Ministry of Municipal and Rural Affairs of the Kingdom of Saudi Arabia (MOMRA) to improve its operational

Year and location	No. of casualties
1990: Pedestrian tunnel	1,426
1994: Jamarat Bridge	266
1997: Jamarat Plaza (eastern entrance)	22
1998: Jamarat Plaza (eastern entrance)	118
2001: Jamarat Bridge	35
2004: Jamarat Bridge	251
2006 (January): Jamarat Bridge	363

Table 1: The table displays the death toll in selected crowd-related disasters, which occurred during the Hajj between 1990 and early 2006.
Source. **MOMRA**

and planning efficiency and the pilgrim experience; most importantly, these techniques helped to prevent crowd-related accidents from late 2006–2007 through 2014. Unfortunately, a crowd-related disaster, which resulted in hundreds of casualties, occurred during Hajj season 2015. However, for this Hajj season, the authors and MOMRA were no longer in charge of the scheduling and routing recommendations for the stoning-of-the-devil ritual. Instead, some of the authors of this paper provided plans for the scheduling and routing of pilgrims for the Makkah metro system. These plans were implemented successfully and safely.

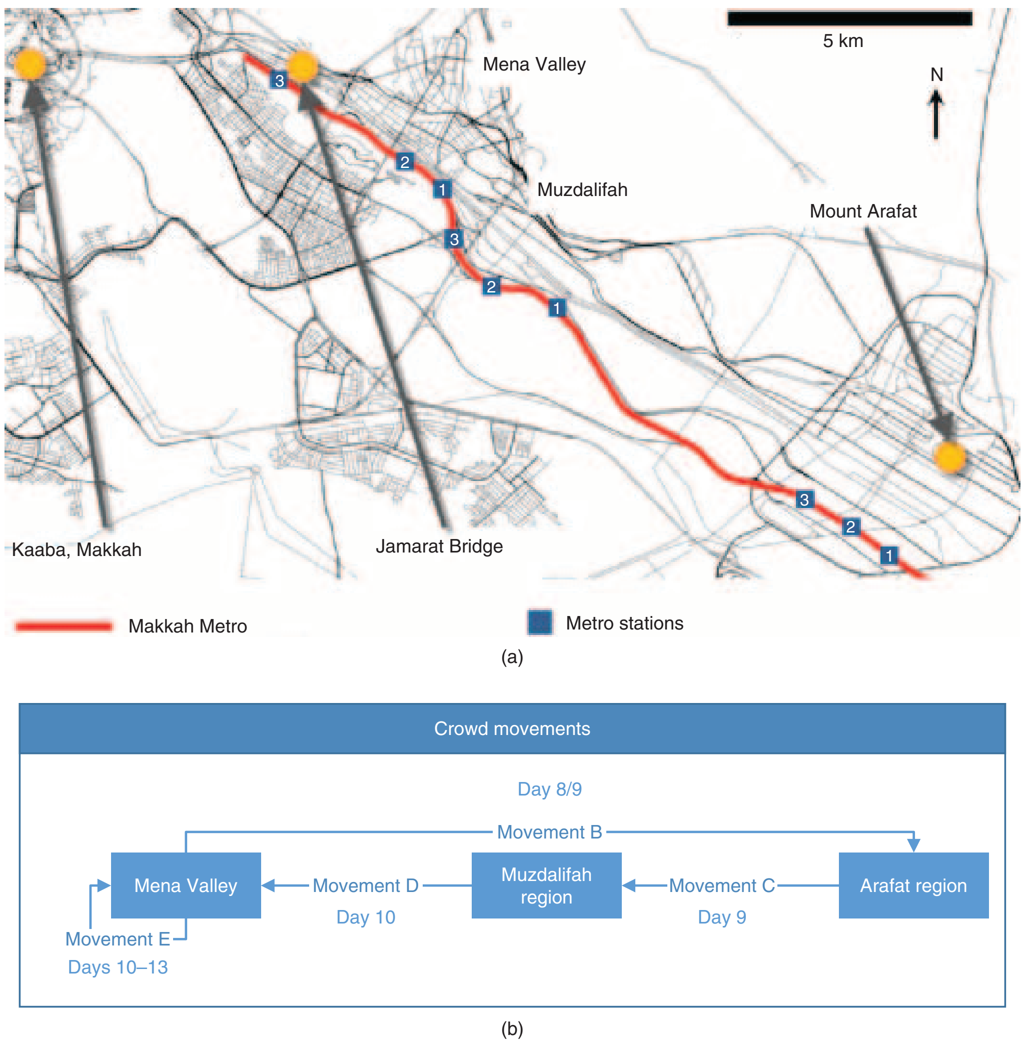


Figure 1: (Color online) (a) The map shows nine metro stations (Arafat 1 to Arafat 3, Muzdalifah 1 to Muzdalifah 3, and Mena 1 to Mena 3; Mena 3 is also called the Jamarat Station). (b) The sequence of crowd movements between the holy sites for Movements B, C, D, and E. During Movement E, the pilgrims move within the Mena Valley. The pilgrims might use the Makkah Metro for these movements.

The Hajj takes place from the 8th to the 13th day of Dhu al-Hijjah, the 12th and last month of the Islamic (lunar) calendar. The Hajj is a religious duty for every Muslim and the fifth pillar of Islam (after testimony, prayer, alms-giving, and fasting). In 1950, fewer than 100,000 pilgrims performed the Hajj; in 2005, the number of pilgrims performing it exceeded two million for the first time.

The map in Figure 1(a) displays the transport infrastructure and the locations of the holy sites. Most of the rituals performed during the Hajj take place in Makkah and the region east of Makkah. To perform the rituals, the pilgrims move between the holy sites; we refer to this as crowd movement (Figure 1(b)).

Figure 2(a) shows the Jamarat Bridge and Figures 2(b)–2(e) show key holy sites.

Upon arriving in Makkah, the pilgrims perform the Tawaf ritual, in which they circle around the Kaaba seven times (Figure 2(d)). On the 8th day of Dhu al-Hijjah, the first day of the Hajj, the pilgrims move from Makkah to their camps in the Mena Valley after sunset (Figure 2(c)). From the evening of the eighth day until noon of the ninth day of Dhu al-Hijjah, the pilgrims move from the Mena Valley to the plain of Arafat (Figure 2(e)), where they pray for the entire day. After sunset and before midnight, they must move to the area of Muzdalifah where they pray and collect pebbles that they will need for the next ritual, the stoning-of-the-devil (Ramy al-Jamarat) at the Jamarat Bridge (Figure 2(a)), which is located on the Jamarah Plaza (Figure 1(a)). The pilgrims throw several pebbles against the three Jamarah pillars representing the devil (Figure 2(b)). On each of Days 3–5 of the Hajj (the 10th day to the 12th day of Dhu al-Hijjah), the pilgrims perform Ramy al-Jamarat. Pilgrims who are still in Mena on the 12th day after sunset must also perform the stoning ritual on the 13th day of Dhu al-Hijjah.

The pilgrims are accommodated in tents in the Mena Valley during the time of this ritual. Thereafter, they leave the Mena Valley and travel to Makkah (Figure 1(b)), where they perform a final Tawaf. Most pilgrims previously traveled between holy sites by walking or by bus. However, since the 2010–2011 Hajj, the Southern AlMashaaer Makkah metro line (Makkah metro) has connected Jamarat, Mena, Muzdalifah, and Arafat (Figure 1(a)).

The Ramy al-Jamarat ritual is particularly crowded (Johansson et al. 2007). Helbing et al. (2007a) found that high-density flows, such as flows with extreme local densities of up to 10 persons per square meter (sqm), can result in a phenomenon called crowd turbulence and can trigger the trampling of pilgrims. To prevent such disasters, high-density flows must be avoided. Indeed, three conditions can result in a disaster: (1) low infrastructure capacity, (2) large numbers of pilgrims, and (3) merging flows, intersecting flows, or counterflows, especially in constrained spaces. By counterflows, we mean flows that move in opposite directions. In particular, if many pilgrims head toward or pass through a location with low infrastructure capacity in a short time, this location can become a bottleneck with high densities and a high risk of crowd turbulence.

Because of specific religious requirements, most pilgrims wish to perform the stoning ritual at specific times. As a consequence, the Jamarah pillars created bottlenecks before the completion of the new Jamarat Bridge. The new bridge can accommodate 480,000 pilgrims per hour (four times more than the old two-story Jamarat Bridge); see the first two figures in Helbing et al. (2007b). Intersecting flows or counterflows increase the number of braking or avoidance maneuvers, which in turn reduce flows. If pilgrims use the same access to and egress from the Jamarat Bridge, counterflows and intersecting flows are likely to occur. During the previous disasters (Table 1), several of these undesirable conditions were typically present.

Approximately two million registered pilgrims are accommodated in the tent camps of Mena (Figure 2(c)). The number of registered pilgrims is limited by the number of visas that the Saudi Arabian government has issued; however, in addition to the registered pilgrims, up to two million unregistered pilgrims, mostly from Saudi Arabia, perform the pilgrimage (Figure 3).

The behavior of the unregistered pilgrims is hard to control. To consider them, some capacity is reserved for unregistered pilgrims in accordance with their anticipated arrival times, which reduces the nominal capacities that are available for the scheduling of the registered pilgrims.

The tents in the Mena Valley used by the registered pilgrims are organized in camps. To address operational issues, the pilgrims within a camp are organized

Figure 2: (Color online) The Jamarat Bridge (a) was constructed between 2006 and 2010; all five stories have been in use since 2010. We show pictures of the following holy sites in the region of Makkah: Jamarah pillar (b), which is embedded in the Jamarat Bridge; the tent city in the Mena Valley (c); Kaaba located in the Grand Mosque in Makkah (d); and Mount Arafat in the plain of Arafat (e).
Source. **MOMRA.**

in groups of approximately 250 pilgrims each. Each group is led by a guide. The accommodations and the transport (including arrival and departure) of the pilgrims are managed by establishments, which are comparable to travel agencies.

Depending on their origin, cultural background, and (or) traditions, the pilgrims have preferred stoning time periods. The (preferred) departure period of a group can be derived from its preferred stoning period. If all pilgrims would perform stoning during their preferred stoning periods, overcrowding would likely occur. Thus, we define peak periods to be when most pilgrims (registered and nonregistered) prefer to perform the stoning ritual. Additional details on

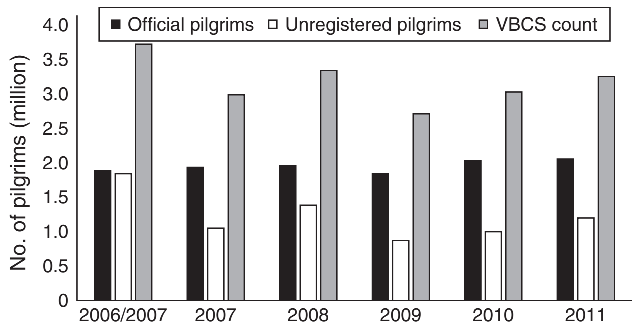


Figure 3: The graphic depicts pilgrim numbers, both registered (official) and unregistered, for the Hajj seasons from late 2006 to 2011. A video-based counting system (VBCS) is used to estimate the total number of pilgrims. ***Source.*** **MOMRA.**

the concepts discussed in this section can be found in Haase et al. (2015).

Operations Research-Based Decision Support System

We developed an OR-based decision support system (ORDSS) that consists of several OR and analytics tools to address crowd management for the Hajj (Figure 4). At its core, it includes a pilgrim scheduler and a crowd-control system.

The Pilgrim Scheduler is an integrated set of mathematical programming approaches to ensure smooth pilgrim flows and a best match with the preferred stoning times of the pilgrims. The core tool for crowd control is a video-based counting system (VBCS) that provides real-time information about infrastructure capacity utilization and forms the basis for an effective warning system. The ORDSS is also used to analyze infrastructural and operational modifications. Its simulation tool (SIM) provides tailored simulation methods to measure the impact of infrastructural modifications on flow conditions. Before implementing a given schedule generated by the Pilgrim Scheduler, we simulate the pilgrim flows based on that schedule to identify potential high-density locations. In addition to VBCS, we employ a radio-frequency identification system for metro ticket inspection (RFID-MTI). At each metro station, the VBCS counts the pilgrims entering the station and the RFID-MTI controls the platform utilization and the number of free-riders. Based on this real-time information, we use an integrated analytics and OR tool for online dispatching (PATCH).

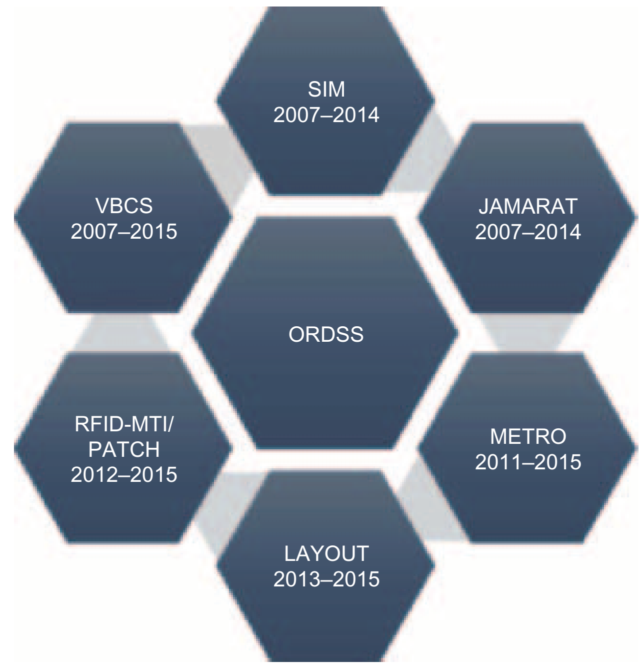


Figure 4: (Color online) The graphic shows each component of the OR-based decision support system (ORDSS) and its date of implementation and use.

The ORDSS described in the sections below is an indispensable tool for strategic (SIM), tactical (Pilgrim Scheduler), and operational (PATCH, VBCS) crowd management during the Hajj.

Pilgrim Scheduler

As we outlined earlier, preventing overcrowding by addressing the conditions that cause it is a key prerequisite to averting disasters. Given a specific infrastructure setup, we can manage such conditions by operating the infrastructure at appropriate utilization levels and by avoiding counterflows and intersecting flows. The main objective of the Pilgrim Scheduler, which consists of the three modules listed next, is to provide a plan for this operation.

(1) JAMARAT: A mathematical optimization approach for assigning a path—a connection of a camp to the Jamarat Bridge (access and egress routes) using streets and (or) the metro line—and stoning times to groups of pilgrims within each camp (Haase et al. 2015);

(2) METRO: A two-step optimization approach to assign camps to metro stations and to assign groups

Group	Solution 1		Solution 2	
	Deviation	Squared deviation	Deviation	Squared deviation
1	0	0	0	0
2	0	0	1	1
3	2	4	1	1
Total	2	4	2	2

Table 2: The data in this table show our evaluation of two alternative solutions for a stoning time assignment based on the deviation from a group's preferred stoning time.

to trips of the metro system during movements B, C, and D; and

(3) LAYOUT: A mixed-integer program (MIP) to design the camp layouts of the station's catchment areas (camps assigned to specific metro stations) in Arafat and Muzdalifah.

JAMARAT: To achieve a high schedule compliance rate, the stoning time preferences of a scheduling group (a distinct combination of day and pilgrim group) must be considered. The day-dependent stoning time preferences are provided as percentage distributions for each camp. We developed a tailored heuristic to determine each scheduling group's preferred stoning time, such that the camp's distribution is considered (almost perfectly) as if we assigned to each scheduling group its preferred stoning period (Haase et al. 2015). The assigned stoning period of a group should be as close as possible to its preferred period. However, we do not assign some groups to their preferred periods if doing so would result in overcrowding in some time periods. For this, we minimize the squared temporal deviation between the assigned period and preferred period. For example, from the two alternative solutions given in Table 2, we select the second one according to our objective measurement. The squared deviations correspond to our objective function coefficients. Therefore, we do not need a quadratic optimization for this part of the pilgrim scheduling problem.

Another objective of our scheduling approach is to avoid high fluctuation (oscillation) in the capacity utilization of the resources. We achieve this by using a set of linear constraints (fluctuation constraints). The resources are the streets, the metro line, and the Jamarat Bridge. Each path requires a set of resources, and several paths might require a given resource. Each resource has a limited capacity per period. The capacity of a resource is expressed as the number of pilgrims that can be served per period without causing congestion. Given a resource, we consider the number of pilgrims that correspond to somewhat more than one pilgrim per sqm as the resource capacity limit. The 100 percent utilization was specified in such a way that it ensured a continuous flow based on the empirical observations in the previous years. Densities higher than 4.4 pilgrims per sqm were considered critical.

Assigning a scheduling group to a specific period is a binary (i.e., yes or no) decision, which we can model easily using binary variables. Each pilgrim group within a camp uses the same path. We also use binary variables to model the assignment of a path to a camp. Our mathematical program contains more than three million binary variables and more than 50,000 constraints. To solve the problem, we ignore the fluctuation constraints in the first step and we minimize the sum of the squared utilization of resources (i.e., we balance the resources as much as possible). In a second step, we consider only the integer constraints for the path-assignment variables. As a result of the objective function, only a few time-slot assignment variables are determined by this step to be noninteger. We fix all relaxed integer variables that are already integer after the second step (i.e., a binary variable that is zero or one is fixed to zero or one, respectively). As a result of fixing the path-assignment variable, we decompose the problem into independent subproblems for each day.

In each step, the optimization problems are solved in reasonable time with GAMS/CPLEX. On a standard personal computer, the CPU time required to run all steps is less than five minutes. Moreover, our fix-and-optimize strategy provides a high-quality integer solution. Haase et al. (2015) provide a detailed description of JAMARAT, including computational studies and validation.

METRO: The Makkah metro connects the holy sites of Jamarat Bridge, Mena, Muzdalifah, and Arafat. Its design capacity is 72,000 passengers per hour and per direction. This corresponds to loading 3,000 passengers per train. Metro operations management estimates that under ideal operating conditions (i.e., without technical failures and with an optimized loading and unloading operation on the platforms), train loading could be increased to about 4,000 people per train. Pilgrims who have purchased metro tickets are located in catchment areas around the stations. These areas are fenced to restrict access to the metro system.

Figure 1(b) shows the major crowd movements within the metro system. The movement from Arafat to Muzdalifah on the evening of the 9th day (Movement C) is particularly difficult to operate, because a religious requirement demands that all pilgrims leave the area between sunset and midnight. If a pilgrim cannot fulfill this requirement, his or her Hajj performance is regarded as incomplete. For the responsible agencies, a failure in the operation of Movement C would be dramatic. The credibility of the ambitious transport project (Makkah metro) would suffer; in addition, MOMRA, responsible for the operation of the Makkah metro, would face complaints and compensation demands from pilgrims who could not complete the Hajj because of delays. Hence, the metro system must move more than 400,000 pilgrims within the 5.5 hours of Movement C in a perfectly organized operation. For comparison, this equates to moving the entire population of Miami, Florida from one point to another in 5.5 hours.

To support the task of dispatching groups toward the metro stations, we implemented a group scheduling system in 2011. Next, we describe the planning problem that we solved in the context of metro scheduling and station assignment.

Metro trains simultaneously leave the three stations in Arafat from the north and south platforms. To ensure an efficient use of the train capacity in this movement, the number of pilgrims must be balanced on the northern and southern catchment areas of each station. The number of pilgrims assigned to each station should be approximately equal. The foundation of a smooth operation of the critical Movement C is laid in the preceding Movement B, in which pilgrims move from the Mena Valley to Arafat. Each station in Mena corresponds to a station in the Arafat region. Because of the alignment and operation of the metro convoys in Movement B, a group's arrival platform in Arafat depends on its departure time from Mena. Pilgrims are usually allocated to camp zones on the same platform side on which they arrive in Arafat. To avoid crossing flows and collisions, crossing one station from north to south (or south to north) is usually not allowed for the groups.

Figure 5: (Color online) The figures show an electronic gate at Jamarat Station (a) and examples of metro tickets (b). Pilgrims eligible to use the metro system are detected by their wristbands when they pass the electronic gate.
Source. **MOMRA.**

By constructing schedules that assign to each group a departure time and a departure station, we can achieve a balanced utilization of stations and platforms in Arafat. The scheduling approach must also consider other requirements. Although balancing is the primary objective during the station assignment stage, our approach also minimizes the distances the groups must walk to the stations. Electronic ticket gates are the entry points for pilgrims into the stations (Figure 5(a)). The Thales Group developed the gates specifically for the Hajj. To allow the antennas of the RFID system at the electronic gates to correctly detect the RFID tags on the users' tickets (Figure 5(b)), a steady flow of pilgrims through the gates is necessary to avoid overloading the short-term capacity of the gates. We consider this aspect in generating the timetables. To ease the loading of the trains at the departure stations, the distribution of passengers must be balanced on the 300-meter-wide platform. We achieve this by balancing the utilization of the electronic gates of each station within the scheduling approach. Finally, when determining the routes of the pilgrims toward the ticket gates, we apply a strict one-way system to avoid counterflows.

The camps are assigned to proximate stations, but some groups might not use the station closest to their camp location for balancing reasons. Internally, each camp is assigned to an electronic ticket gate at the station to balance platform utilization and support the operation of the electronic ticket gates. We implemented the metro user scheduling system using mixed-integer programming with GAMS/CPLEX. We use one MIP to assign groups to stations and gates, and a second MIP to assign groups to trips of the metro. The scheduling groups assigned to a particular station are segmented by their destination gates. The segments of a station are scheduled in parallel for each train departing from the station.

We provide MOMRA with timetables and maps that display the paths pilgrims of a given camp should use. To simplify the distribution of the plans for MOMRA and the Ministry of Hajj, we launched a website (http://hajjschedule.info/) in 2012 to provide timetable information (Figure 6), maps, briefing videos, and leaflets to all agencies. Moreover, the scheduling results are used to subsequently report about the scheduling compliance of metro users and to provide real-time monitoring during the days of the Hajj.

LAYOUT: A few days before the Hajj begins, agencies of the establishments set up a tent city in Arafat for millions of pilgrims to accommodate them during their stay in the plain of Arafat on the 9th day of the Hajj. Therefore, we define areas for the camps in the plain

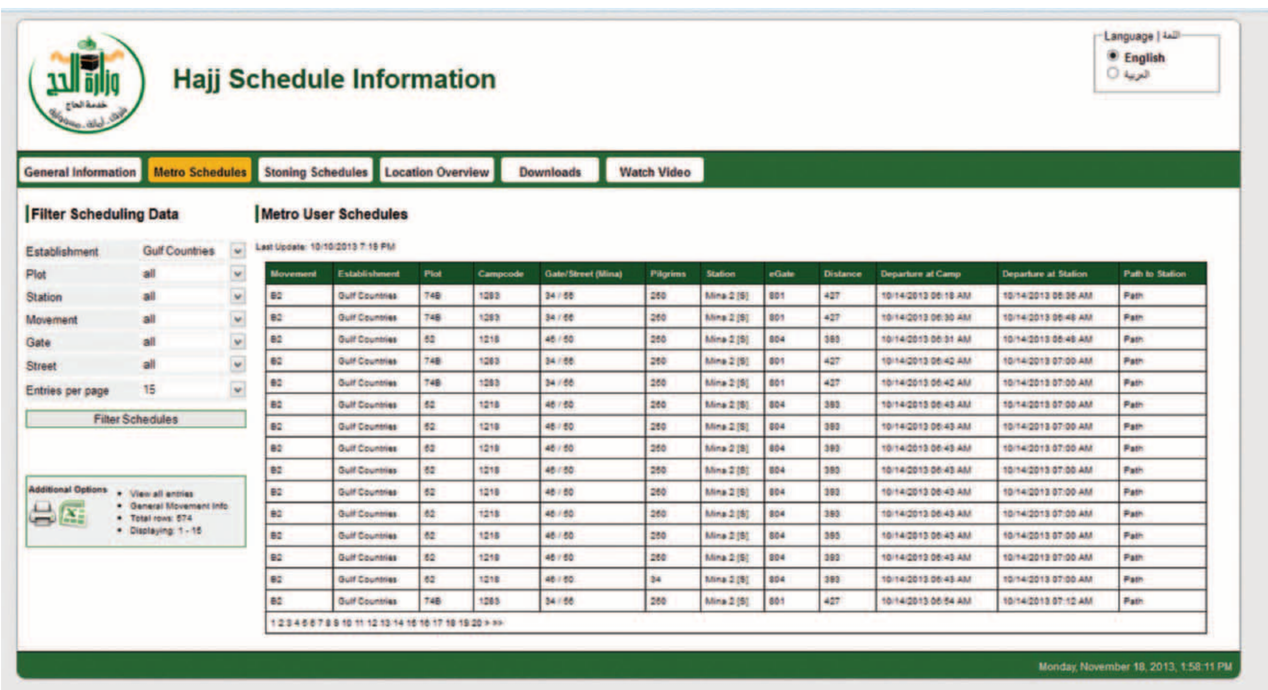


Figure 6: (Color online) This example shows an excerpt of a schedule that provides important and easily accessible information (e.g., departure times from specific metro stations) to the guides and pilgrims.

of Arafat. Pilgrims who arrive on the north (south) platform of a station are housed in camps on the north (south) side of the station. Because of wide streets and walking roads, restroom houses, fences, flood channels, raised plains, and engineering considerations, we divide each side into subareas. We partition the area of Arafat into camp areas to accommodate the pilgrims during Movements B and C. For all metro users who arrive in Arafat, the departure stations and platforms must match their arrival stations and platforms. Therefore, the pilgrims should be located near their arrival stations. For crowd management, pilgrims who arrive early should be located further away from the station than pilgrims who arrive later. Taking into account the distance from the metro station and the arrival time, we derive a priority measure for each organizational unit, service-office camp (i.e., distinct combination of a camp and a service office, which is an organizational subunit of an establishment), and subarea. In general, the further away a subarea is from the arrival station of a pilgrim's service-office camp, the larger the priority value is; however, the actual priority value depends on the arrival time of the pilgrims of the service-office camp. The more pilgrims in a service-office camp, the more square meters the camp requires. We developed an assignment problem in which we minimize the sum of the priority values. Constraints guarantee that each service-office camp is assigned to at most two adjacent subareas. Finally, we consider capacity constraints such that all pilgrims in a service-office camp can be accommodated in the respective area. Because of the objective function and the set of assignable subareas of an office, contiguity constraints are not necessary (Haase and Müller 2014). Therefore, the problem formulation becomes much easier to solve using standard solvers (Drexl and Haase 1999). The results are only a starting point for subsequent, more detailed layout-planning activities in cooperation with the Ministry of Hajj, Saudi Arabia. This approach significantly accelerates the process of generating a final solution for the Arafat camp layout problem.

Simulation

Before implementing a schedule, we use computer simulations to study its impact. For this, a simulation tool was developed to analyze the pilgrim flows generated from a schedule based on the Lighthill-Whitham-Richards (LWR) model (Coscia and Canavesio 2008). The simulation predicts changes in the local density of each road segment over time. We assume that the velocity of pilgrims is given by the local density in a segment. Variants of the model differ only in the form of the chosen velocity-density function, which determines the shape of the flow-density diagram. Therefore, we employ the flow-density diagram to determine the local pilgrim flows for each segment. For

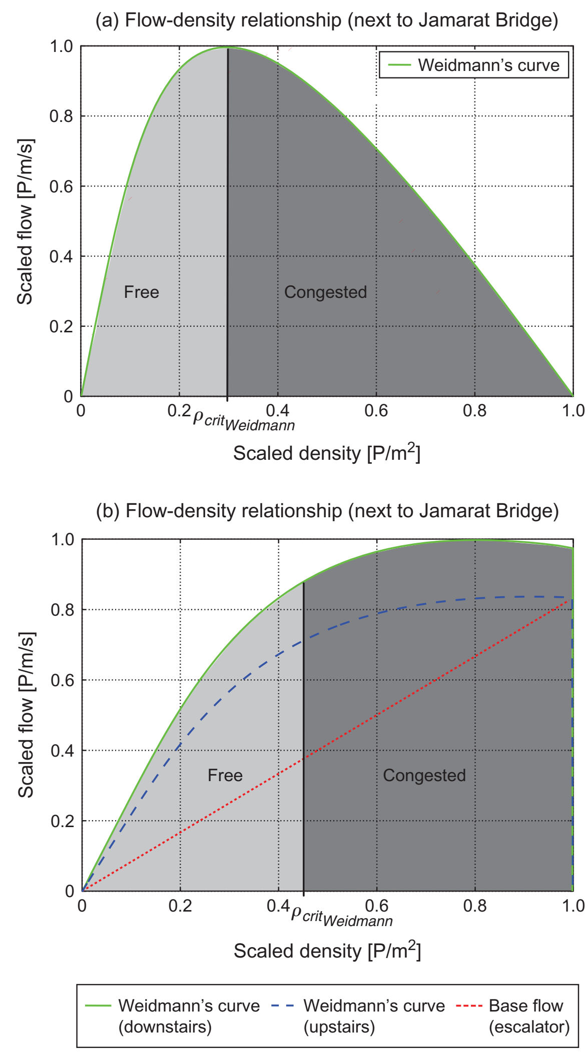


Figure 7: (Color online) Schematic illustration of scaled flow-density diagrams for walkways (a) and escalators (b). The index ρ_{crit} marks the local density where the free-flow conditions end. The curves scale Weidmann's internationally established flow-density relationships. When used in computer simulations, the curves are adjusted to empirical data observed during the Hajj.

the description of the expected pedestrian velocities, we use an empirically fitted curve (Johansson et al. 2008). Generally, the local flow increases gradually up to a critical local density (Figures 7(a) and 7(b)), at which point the capacity of the considered segment is exhausted. At this point, the local flow starts to decrease, because no space is available in the segment, and it becomes congested. The flow-density diagram depends on the type of the segment. For example, the flow-density diagram in Figure 7(b) is fitted to empirical data about escalators, and we must consider the movement of the escalator. To determine the number of pilgrims who move from a segment into the adjacent segment, we use the supply-demand method (Daganzo 1995).

A core task of the simulation tool is to identify potential areas and periods of high crowd densities. Figure 8(a) shows a snapshot of a simulation run for the year 2010. For the Al-Moaisim tunnel, we identified critical densities for several periods. We could not find a schedule to resolve this problem, because of the limited infrastructure capacity at this location. Using the simulation tool, we were able to identify locations of high risk for overcrowding for the entire Mena Valley (shaded locations in Figure 8(b)). As a result, MOMRA implemented several infrastructure improvements. For example, to increase the capacity in the Al-Moaisim tunnel area, MOMRA built a new parallel tunnel, the Shoaibain tunnel, in 2012. In 2009, only some floors of the new Jamarat Bridge were in operation; therefore, Jamarat Bridge was also identified as a potential risk area. Since 2010, all five floors have been in operation, and the Jamarat Bridge and the surrounding Jamarat Plaza are no longer considered risk areas. In 2009, we identified the King-Khaled tunnel and an area with crossing flows in the middle of the Mena Valley as bottlenecks. To address this, we changed the routes of certain paths and the feasible assignments of camps to paths to make these areas safe if the schedules and routing are followed. The results of the simulation show that the Pilgrim Scheduler provided well-balanced pilgrim flows from 2010 to 2014.

In addition to the simulation approach to identify areas of potentially high densities, we employ microscopic simulation tools to analyze certain infrastructures in more detail (Fellendorf 1994). A unique feature of such microscopic simulations is that they can consider interactions between individuals (i.e., pilgrims).

To analyze the boarding of more than 3,000 pilgrims per stop at a train station, we apply the simulation tool VISSIM and its plugin Viswalk. This software uses the social force model as its simulation core (Helbing et al. 2005). We were interested in the pilgrim flows inside the Mena 1 metro station. In particular, we analyzed whether specific schedules would cause overcrowded platforms. These simulations allowed us to verify that the schedule of choice would lead to a smooth and consistent infrastructure load. Moreover, we were able to optimize the pilgrim flows inside the metro station.

Crowd Management and Control

If the pilgrims adhere to the predetermined schedule and use the officially assigned paths, they can avoid dangerous high-density crowds. Metro operation time during Movements B, C, and D depends directly on the service offices' compliance with the schedules generated. A high compliance rate with the precomputed schedules results in a highly efficient metro operation. If pilgrims do not adhere to their schedules (i.e., if they arrive early or late), they might intermingle and form long waiting queues. In addition, many of the ramps and streets are in the sun during daytime hours, making waiting in long queues stressful and potentially hazardous, and overcrowded queues can hinder the timely arrival of first aid.

Therefore, controlling and managing pilgrim compliance with the predetermined schedules in real time is a central aspect of crowd management. The ORDSS integrates an RFID-technology-based live monitoring subsystem (RFID-MTI), a video-based counting subsystem (VBCS), and a smartphone-based dispatching report system (PATCH). In cases of congested conditions, pilgrims might be redirected or groups may be kept in their camps until the congestion is resolved. In our post-Hajj evaluations, we use control data in two ways. First, we use it to analyze infrastructure utilization peaks and to reevaluate pilgrim time preferences. Thus, each Hajj season's data contribute to a better parameterization of the scheduling approach for the next season. Additionally, in our post-Hajj reports, we provide detailed statistics on the scheduling compliance of each service office. We recommended implementing a system to penalize service offices that repeatedly fail to comply with the optimal computed schedules.

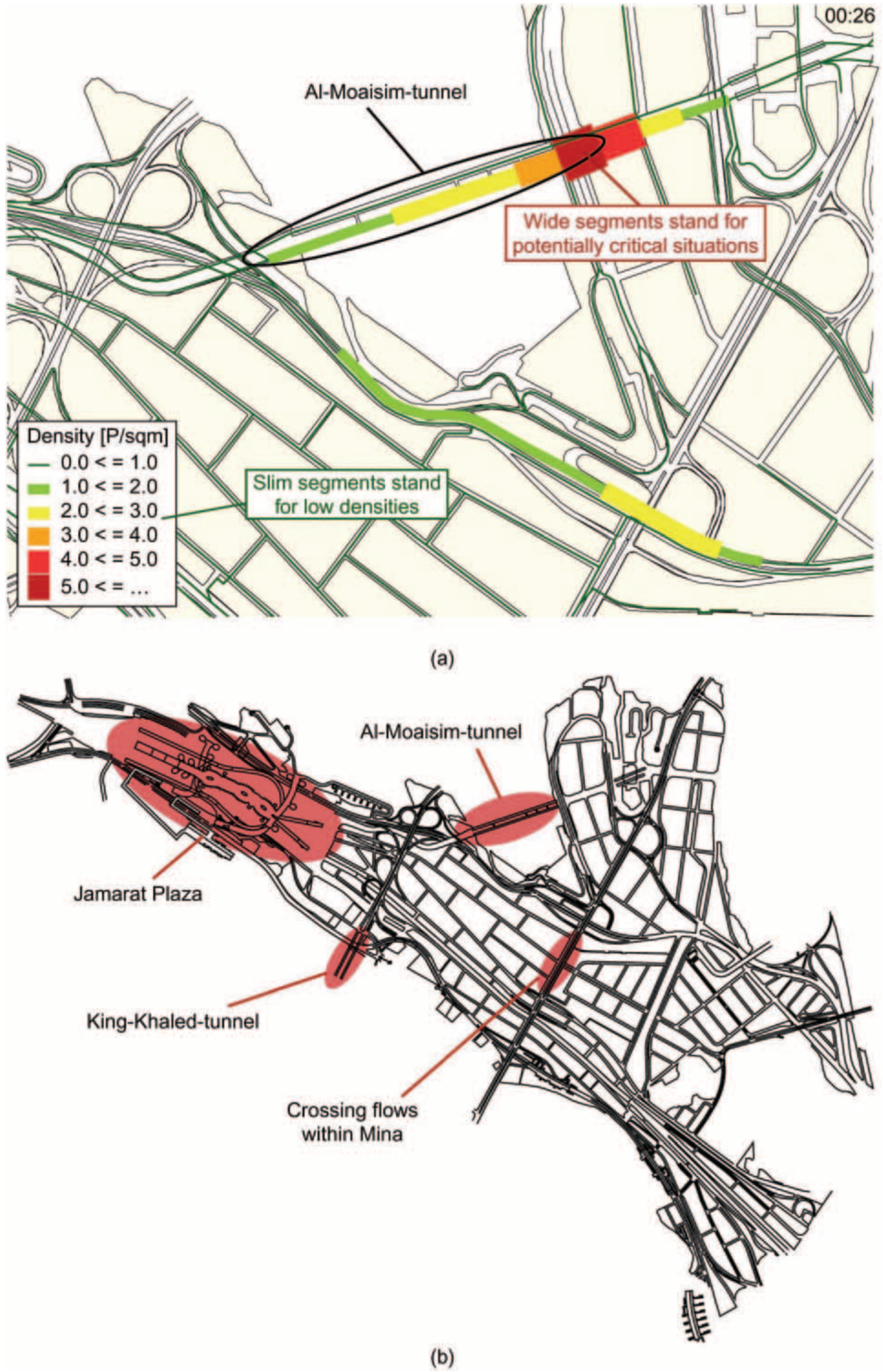


Figure 8: (Color online) The maps identify locations of critical densities using computer simulation (SIM). Locations where the simulation yielded densities of more than four pilgrims per square meter were considered to be potential areas of risk, considering safety margins. Subsequent to our risk analysis, various measures were taken to reduce these risks (see main text).

VBCS: The Jamarat Bridge, the main streets in the surrounding area, and the metro stations are observed by a network of CCTV cameras. The images taken by the cameras are used by tracking software to calculate the difference between the inflow and the outflow of pedestrians in the observed area (Johansson et al. 2007). By constantly measuring these differences, increasing or decreasing crowd densities can be detected early.

The system allows one to compare the detected flow of pilgrims with the available capacity of the corresponding infrastructure. Based on empirical data from previous Hajj seasons, the VCBS predicts the possibility of overcrowding based on the actual density in the respective area. This helps security forces to assess the potential risk of overutilization of the infrastructures observed and directly supports decisions about redirecting pilgrims (Johansson 2009).

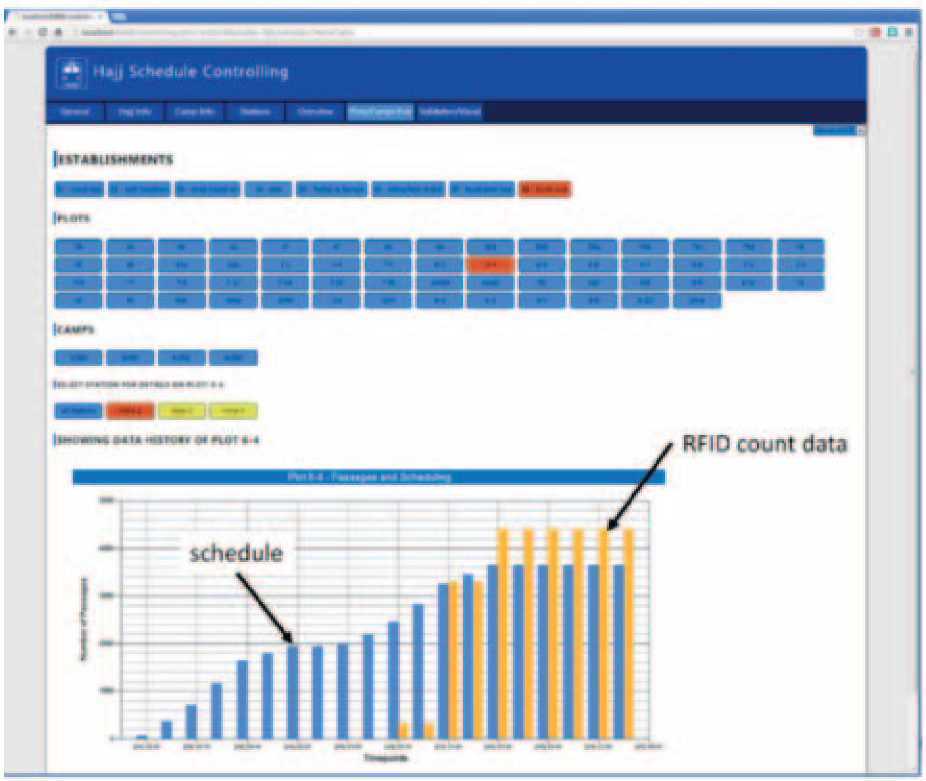
RFID-MTI: We use RFID-based data analysis to monitor metro operations during Movements B, C, and D. Service offices can purchase RFID-tagged metro tickets for their pilgrims (Figure 5(b)). The distribution of about 400,000 metro tickets to more than 200 service offices in less than four business days is a significant logistical challenge for MOMRA. Therefore, we implemented a distribution heuristic to minimize the number of ticket boxes that the distribution team must open and distribute to the various service offices. Each ticket has a serial number. For example, tickets for Metro Station Mena 1 have the numbers 1–130,000, and tickets for Metro Station Mena 2 have the numbers 130,001–260,000. The manufacturer delivers the tickets in boxes with five batches of 100 tickets per batch. Initially, the camps are sorted according to their corresponding service office and the station to which the camp is assigned. Consider a camp that houses a large number (e.g., more than 1,000) of pilgrims. For each establishment, we perform three steps: In step 1, we assign whole boxes to the camps (e.g., two boxes to a specific camp). In step 2, we split the boxes into batches and assign whole batches to the camps (e.g., one batch to a specific camp). In step 3, we split the batches and assign single tickets to the camps (e.g., 15 tickets to a specific camp). Our involvement in this process reduces ticket distribution costs and also gives us priority access to the ticket distribution data. By linking this distribution information with the schedule's organizational data, we developed the RFID-MTI subsystem.

When pilgrims pass through the station gates (Figure 5(a)), they are counted in a two-step process. First, the RFID tag on the pilgrim's ticket is read. Then a camera registers that pilgrim's passage. We receive RFID-detection and camera-detection data from the stations' databases. By combining the number of pilgrims counted, pilgrim-scheduling data, and ticket-distribution information, we can compute punctuality statistics for camps and establishments. By comparing camera and RFID count data, we also calculate the estimated number of free-riders. Our analysis is visualized in the form of thematic maps, charts, and tabular data for users (for example, station management and dispatching teams) to employ (e.g., via spreadsheets or handheld devices). The system monitors RFID counts from RFID-MTI and pilgrim counts from VBCS, and compares them with the number of scheduled pilgrims (Figures 9(a) and 9(b)).

Using the new Pilgrim Scheduling system, which was in operation for the Hajj seasons between 2012 and 2014, dispatching operators can monitor the dispatching status of any camp in real time. As a result of our efforts, crowd-management measures and the dispatching operation can now be targeted at specific camps to address dispatching problems, in contrast to previous years.

PATCH: Pilgrim-dispatching teams report on dispatching times and dispatching problems at their assigned camp sites. Moreover, they survey the pilgrim groups about their preparation hours, the time during which the pilgrims prepare for the movement (e.g., pack water and food), before the crowd movements begin. For each task, dispatchers fill out specific forms on paper. MOMRA has begun developing a smartphone-based reporting system, which will replace the paper forms it uses in its recent reporting system. Although the system has been developed and integrated into ORDSS, it is not yet in full operation. Dispatching staff members use smartphones to transmit their reports to the scheduling database. A Web service processes and combines the data with the existing schedule data, which the Pilgrim Scheduler generated. Although all reporting data are available in tabular form to the operators, we also provide visual user interfaces that are easy to navigate for the crowd-control operator.

(a)



(b)

Figure 9: (Color online) The screenshot in (a) shows a monitoring website that uses live RFID and camera-detection data. The data are used to display scheduling compliance information in real time. Using multiple filters, the user can see timeline data of the number of pilgrims planned and the number of pilgrims detected for specific combinations of pilgrim groups (e.g., plot, camp) and location (e.g., stations, electronic ticket gates). (b) Shows a selection of data from Establishment South Asia, Plot 6–4, at Station Mena 1.

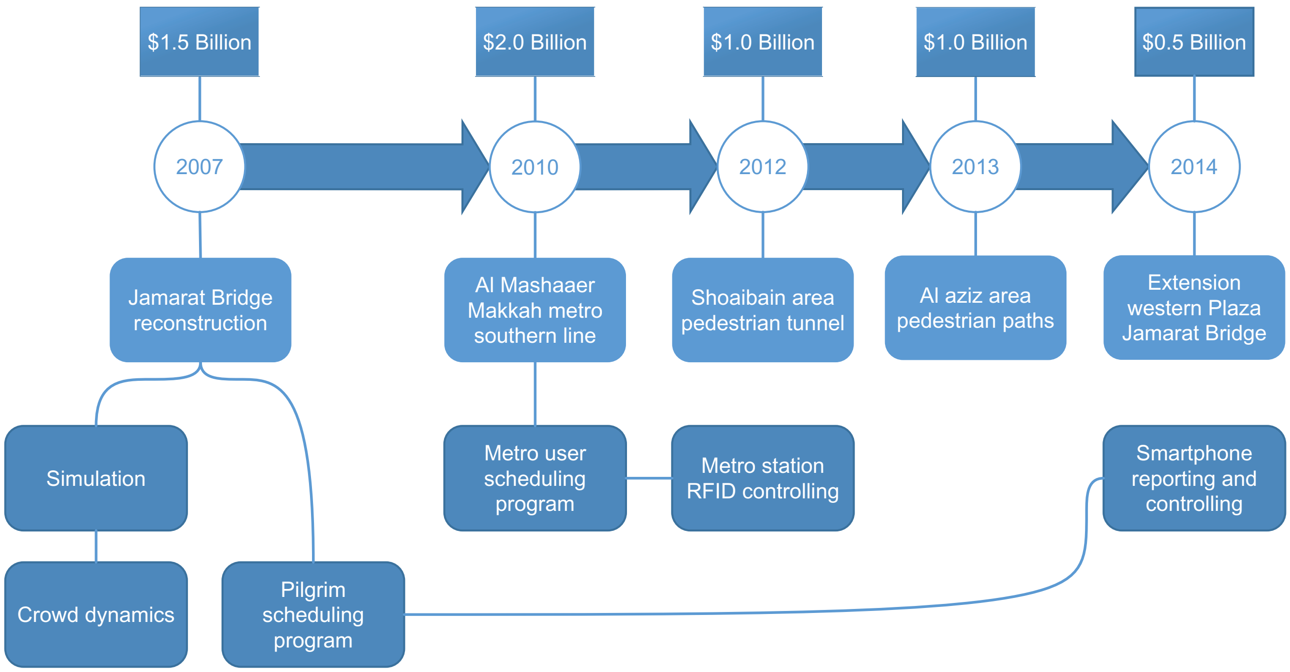


Figure 10: (Color online) The graphic shows the project history and timeline of infrastructure improvements and corresponding crowd-management tools.

The user interface also provides direct access to the Jamarat pilgrim schedules, contact information, and dispatching status for each camp.

Future development efforts in this project include the integration of an automated subsystem that assigns dispatching tasks to dispatchers at a camp site based on GPS coordinates and the dispatching status of that camp.

Implementation and Impact Through 2014

Until January 2006, many tragic crowd-related disasters occurred during the Hajj. In the aftermath of the accident in 2006, MOMRA embarked on an endeavor to prevent crowd-related disasters by employing the most current analytics and OR tools to address crowd dynamics. Figure 10 highlights the projects that comprise this endeavor. Improvements in infrastructure and operations as well as a novel crowd-management system helped to prevent crowd accidents between 2007 and 2014.

How was all this accomplished? MOMRA replaced the old two-story Jamarat Bridge with a new five-story building, which substantially increased the capacity of the infrastructure. Computer simulations were used to optimize the shape of this bridge, and the layout of the street network and the Jamarat Plaza (in front of the bridge). A new crowd-management system was developed to monitor pilgrim flows (VBCS), and we generated schedules for the stoning ritual (JAMARAT). These developments resulted in improved pilgrim scheduling, new real-time pilgrim-flow monitoring, a one-way system for the Jamarat Bridge and the surrounding area (Figure 11), infrastructural separation of flows on the Jamarat Plaza (Figure 12), and the installation of separate emergency lanes. Helbing et al. (2007b) provide details.

As of December 2006, the new Jamarat Bridge had only two levels. Therefore, its capacity was no higher than in previous years. Nevertheless, we achieved a safe Hajj in December 2006/January 2007, although it was one of the most attended Hajj seasons. We accomplished this by implementing the ORDSS, a novel crowd management system. ORDSS is based on the

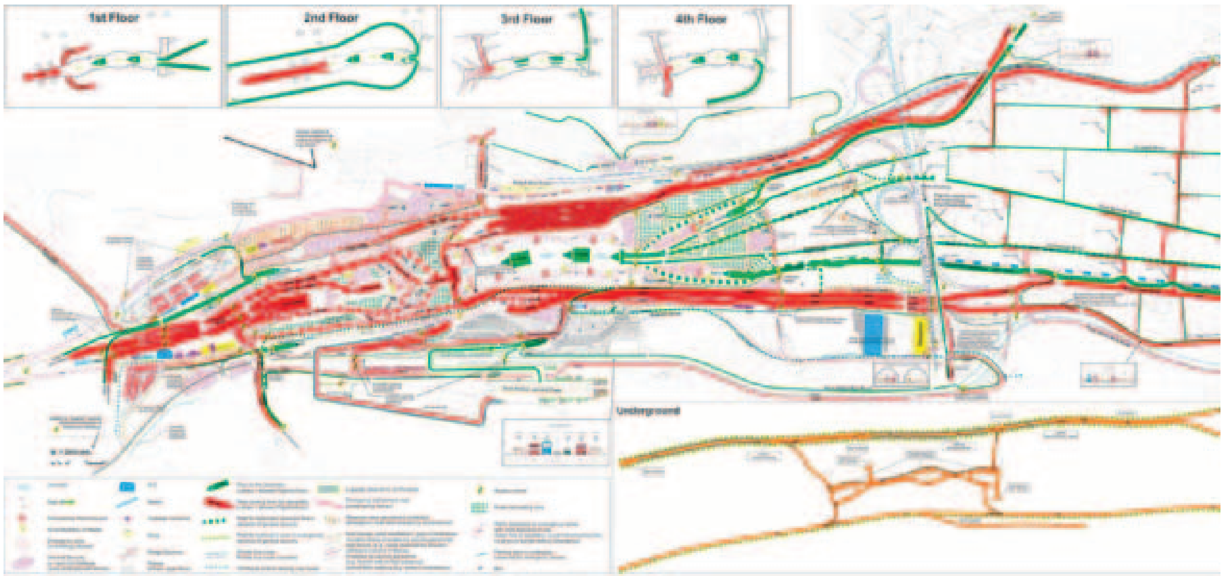


Figure 11: (Color online) The figure shows the one-way system we developed in cooperation with Ingenieurgruppe IVV, Aachen.
Source. **MOMRA.**

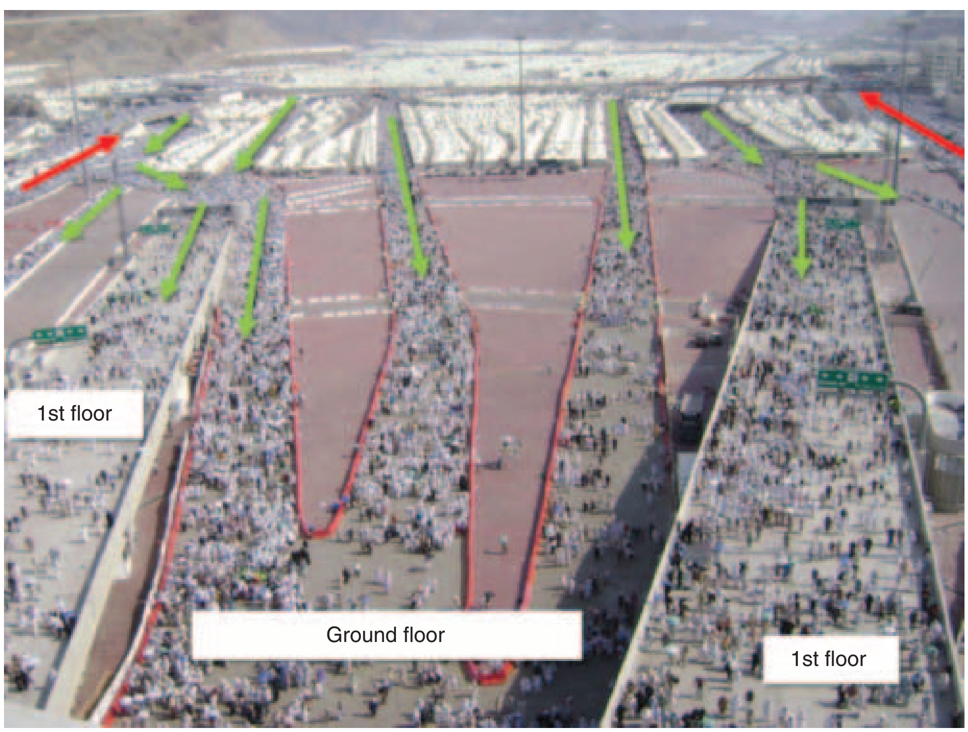


Figure 12: (Color online) This picture, which was taken in 2014, illustrates the separation of pedestrian flows. The inner walkways (arrows pointing downward, i.e., from the tent city) are used by pilgrims accessing the Jamarat Bridge. The outer walkways (arrows pointing upward, i.e., to the tent city) are designated paths for pilgrims leaving the Jamarat Bridge.
Source. **MOMRA.**

application of sophisticated OR methods and computer simulation tools for the assessment of pilgrim flows. We made the most significant improvements by avoiding crossing and counterflows, and by applying the Pilgrim Scheduler.

The analysis of pilgrim flows by computer simulation proved that separating flows by infrastructure and operation can greatly improve flow conditions. The Pilgrim Scheduler enabled a more balanced utilization of the five levels of the Jamarat Bridge. It also helped to increase the efficiency of the Makkah metro, such that more pilgrims used the more environmentally friendly metro system rather than buses. Additional methods included measuring street capacities, based on viewing security camera images, and rerouting pilgrims in cases of high utilization. This novel approach allowed MOMRA to improve pilgrim safety and comfort and to build additional infrastructure (e.g., the Shoaibain tunnel).

Based on the analytical results of VBCS, RFID-MTI, and SIM, the establishments could see that adjusting the feasible stoning periods, as proposed by the Pilgrim Scheduler, can generate more balanced schedules.

Conclusion

In summary, we believe that many challenges of large crowd gatherings can be addressed by using innovative methods of systems management and design, if advanced OR methods are combined with the use of modern information systems and the execution of sound crowd management. For the Hajj seasons 2007 through 2014, for which we provided the schedules and path assignments for the stoning ritual, the Hajj was a safe mass gathering. Although the Hajj is unique, the methods developed may be adapted to other mass gatherings, such as a world fair, a world youth day, or large sports and music events (Kassens-Noor et al. 2015).

Nevertheless, as the sad crowd-related disaster during the Hajj in 2015 shows, a Hajj season where we were not responsible for the scheduling and path assignment of the stoning-of-the-devil ritual, it may never be possible to completely eliminate all risks at complex mass gatherings. Despite major investments in improved infrastructures and sophisticated information systems in and around Makkah, some human factors, such as the behavior of unregistered pilgrims and the compliance of registered pilgrims with their schedules and dedicated paths, are currently hard to control. Despite the difficulty of these challenges, large investments are gradually being made to implement the measures previously proposed by experts.

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