Optimizing Shuttle-Bus Systems in Mega-Events using Computer Modeling: A Case Study of Pilgrims' Transportation System

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***Abstract*—Mega-events are held in a city, or more, during a limited time, which requires special attention to the infrastructure and the offered services. The Hajj event, hosted in Makkah - Saudi Arabia, is considered as an excellent example of religious mega-events. The field of computer modeling and simulation is one of the main technical tools that help in developing and understanding the risks of crowds and studying the safety means during organizing of many major events in the world. This paper focuses on using computer simulation to optimize the pilgrims' shuttle-bus transportation system in Holy Sites (Mashaaer), as a case study of optimizing shuttle-bus Systems in Mega-Events using computer modeling. The objective of paper is to develop a model of the shuttle-bus transport system to give insights of the advantages of the use as an alternative for transporting pilgrims as well as to provide decision makers with a tool that could be used to select the best parameters of the system for the most efficient operation. For this purpose, pilgrims' evacuation time, traffic congestion and average trip time, from Arafat to Muzdalifa, are identified as the performance measures for evaluating the proposed transport system. The conducted simulation can be used to assess the current systems, recommend changes to the systems, and offer indicators and readings to assist decision makers.**

Keywords—Computer modeling; simulation; optimization; shuttle-bus systems; mega-events; hajj

I. Introduction

Mega-events are considered as large-scale events attended by huge numbers of visitors. In addition, they have been getting much attention as key ingredients in tourism for many destinations [1]. Organizing a mega-event has a great impact on the hosting cities, which requires special attention to the infrastructure and the offered services [2].

In order to classify an event as a mega event, different criteria can be considered, such as duration, scale, number of visitors and importance of the event. Among the famous events that can be considered as mega-events are the Olympic Games, the World Expo and the Football World Cup [3], in addition to some religious festivities.

The Islamic pilgrimage (Hajj) event, which occurs once a year and is hosted in Mecca KSA, is an excellent example of religious mega-events.

The Hajj organizers aim at allowing the best possible number of Muslims to perform Hajj to the fullest; and providing the best services before, during and after their visit to Mecca. Transportation is an important service that is offered throughout the entire year and especially during Hajj days. Improving the quality of transportation services requires the use of modern techniques to raise the efficiency of operations and improve services.

Hajj is a set of rites unchanged for 14 centuries that takes place from the 8^{th} to 12^{th} (or in some cases 13^{th}) of Dhul al-Hijjah, the 12^{th} month of the lunar year. On the 8^{th} of Dhul al-Hijjah, pilgrims confirm their intention to make the pilgrimage. After Fajr prayer on the 8^{th} of Dhul al-Hijjah, the pilgrims proceed to Mina where they spend the whole day. The next morning (The 9^{th} of Dhul al-Hijjah), they leave Mina to go to Arafat, where they supplicate and seek mercy of Allah. Pilgrims leave Arafat for Muzdalifa after sunset. After returning from Muzdalifa, the pilgrims perform symbolic stoning of the pillars (Ramy al-Jamarat). On the same or the following day, the pilgrims revisit the Haram Mosque in Makkah for Tawaf al-Ifadah. The night of the 10^{th}, 11^{th}, and 12^{th} of Dhul al-Hijjah are spent back at Mina, where the same process of stoning of the pillars takes place. Finally, before leaving Mecca, pilgrims perform a farewell tawaf called Tawaf al-Wadaa. Fig. 1 illustrates the route taken by pilgrims on their journey and the relative proximity between the Holy sites.

The constraints of time (from the 8^{th} to 12^{th}/13^{th} of Dhul al-Hijjah) and area (Haram, Mina, Muzdalifa, and Arafat) pose different challenges for Hajj authorities responsible for controlling traffic and crowd movements of pilgrims. Such challenges further increase with the steady increase in the number of pilgrims each year.

The restricted times for pilgrim movements between Holy sites suggest that carefully planned pilgrim services are required to be aligned in accordance with such movements. In particular, one of the most important pilgrims' services is transportation.

During the past Hajj seasons, many transportations operational strategies, including regular buses, shuttle-bus, train, or on foot (walking), were successfully experimented between the Holy sites in Makkah.

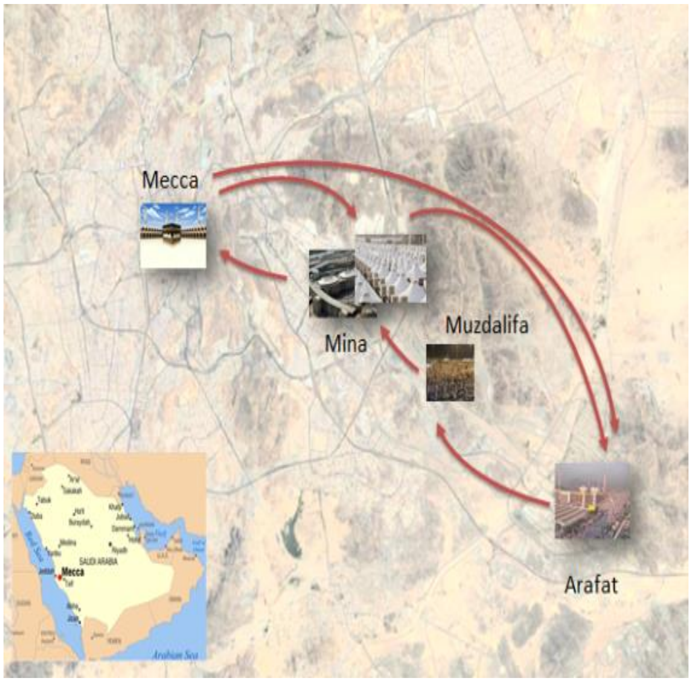


Fig. 1. The route of Hajj journey.

The Saudi Ministry of Transportation first reported on the idea of using shuttle-buses to transport pilgrims between Arafat and Muzdalifa. In the following years, the shuttle-bus project was extended to include the Muzdalifa–Mina roadway and presently continues to operate on the two segments of Arafat–Muzdalifa and Muzdalifa–Mina [4].

Due to the steady increase of number of pilgrims, which may reach five million by 2030, an optimized transportation system is of a high importance. This paper aims at utilizing computer modeling and simulation to study the effectiveness of the pilgrims' shuttle-bus transportation system in Mashaaer Holy Sites. It focuses on using computer modeling to optimize pilgrims' shuttle-bus transportation system for the path from Arafat towards Muzdalifa (Nafrah). More specifically, the paper focuses on the path of pilgrims of Turkey and Muslims of Europe, America, and Australia. This model can be used for the planning and analyzing all Hajj transportation operations. The results of the simulation may be used to assess the effectiveness of the current system and to suggest changes that might be made. Hence, the designed model can be used for optimizing the pilgrim's transportation system with respect to different parameters.

The paper is organized as follows. Section II discusses the literature review. Section III presents the proposed computer modeling of the shuttle-bus system, while results and discussions are presented in Section IV and V respectively. Conclusions are drawn in Section VI.

II. Literature Review

Several research studies investigated the research issues associated with pilgrims' transportation planning and the deployed shuttle-bus project [5], [6].

In [7], an integrated solution to the problem of pilgrimage transportation control while tracking the shuttle-bus from its starting point till its final destination was proposed. The system is designed to work in an environment where vehicle and passenger identification is required, namely at check points, in order to speed up the checking process with best quality services. In the designed system, buses are identified using RFID tags, while passengers boarding or getting off the bus are identified on the basis of RFID cards they have and finger identification.

In study [8, 9], a tool was created to assist in planning the shuttle-bus service operation configuration during Hajj using an analytical approach. With the use of this tool, the shuttle service between Arafat and Muzdalifa can be run with the fewest possible buses and cycles. It uses GPS data to gather information about the shuttle-bus service, including pick-up and drop-off timings, travel times along the path, and the number of pilgrims.

The research reported in [11] presents a simulation study of the 1422H Hajj season shuttle-bus transportation system using the Arena simulation system, with the goal of understanding of the characteristics and limitations of the system, by examining bus routes, dispatching mechanisms, and loading/unloading scenarios on system performance. During this Hajj season, approximately 160,000 pilgrims used the shuttle-buses, and 542 buses were used to transport pilgrims from Arafat to Muzdalifa. The paper suggested that in order to maintain a reasonable evacuation time, the number of buses should not be decreased below a limit of about 500 buses.

An approach in [12] is based on a stochastic simulation model to design a shuttle-bus system to transport pilgrims along the entire Arafat and Muzdalifa segment roadway, using logistics features of ProModel simulator. The model is used to estimate the number of buses needed to transport pilgrims at the shortest possible evacuation time with the least amount of congestion, as well as the number of bus stops needed to accommodate pilgrims. To evacuate Arafat in six hours, the study offered an expanded plan with 3160 buses and 740 bus stations.

A number of research papers addressed the optimization of shuttle-bus systems. The research in [14] examined the optimization of a local shuttle route. It creates a solution to the optimal routing design problem in order to minimize overall cost, which includes user and supplier costs, while taking budgetary restrictions and demand for passenger traffic into account. Both a genetic algorithm (GA) and a depth-first search algorithm (DFS) are used to accomplish this.

A hybrid genetic algorithm is used in [15] to solve a shuttle-bus route optimization model. The travel time reliability estimation approach is based on back propagation (BP) neural networks, and the optimization model is built with operational reliability maximization as its primary goal.

A structure for an optimization model that maximizes the general satisfaction of users and public transit businesses was presented in [16]. A hybrid intelligent optimization technique is utilized to solve the optimization model, which is based on meeting the passenger journey time requirements and reducing the cost-of-service operations.

On a case study of a university shuttle-bus, the research in [17] employs the Artificial Neural Network and Support Vector Machine algorithms for the optimum journey time prediction with a lower error rate. It is also used to suggest appropriate pathways for the selected scenario.

In study [18], an optimization modeling approach based on simulation to assist airport shuttle operators in deploying electric vehicles efficiently was suggested. In order to achieve predefined objectives, the suggested approach uses an event-driven simulation model, Airport Shuttle Planning and Improved Routing Event-driven Simulation (AS-PIRES) [19], to propose an optimization model that determine the battery capacity, charging power, and number of chargers.

In study [10], a transport planning approach that is adopted for the Summer Olympic Games (SOG) and identifies lessons learned for planning of the Hajj/Umrah was explored. It described the context for each event and the nature of transport demand and supply and outlines the transport planning approaches used.

When planning a community shuttle service, the optimal stop location and route can help to reduce the walking distance of passengers and the route length. In study [13], a discrete optimization problem was proposed to make a trade-off between the walking distance of passengers and route length.

III. Modeling the Shuttle-Bus Transportation System in Arafat-Muzdalifa Area

A. Problem Formulation

The issue addressed in this study focuses on computer modeling of the shuttle-bus transportation system for pilgrims on the route from Arafat to Muzdalifa (Nafrah), in particular the route taken by Muslims from Turkey and other parts of Europe, North America, and Australia. Fig. 2 depicts the shuttle-bus route from Arafat to Muzdalifa that is taken into account in the proposed model.

The shuttle-bus transportation system in Arafat-Muzdalifa area is responsible for transporting the pilgrims from loading stations in Arafat (L_{SN} loading bus-stations) to unloading stations in Muzdalifa (U_{SN} unloading bus-stations). In Arafat, the pilgrims are moved to the bus stops in groups, each of fifty pilgrims, and loaded into the bus at that stop. When the Nafrah starts, the first group of buses departs Arafat taking pilgrims towards Muzdalifa and the following group is released to the bus stops. In Muzdalifa, buses unload the pilgrims at the pre-assigned bus stops. The shuttle-bus transportation network utilizes a dedicated two-lane bus road, where bus stops are constructed on the roads' shoulders.

The goal is to complete the evacuation of the designated number of Turkish pilgrims - roughly 240000 pilgrims - within the Nafrah's allocated time frame, maintaining the bus-stations capacity.

In order to complete evacuating the designated number of pilgrims, there is a need for a buses batch size (N), which is the overall number of buses dedicated for the transportation of pilgrims. The number of buses in a batch should be kept to a minimum both economically and to prevent excessive traffic congestion on the roads. In addition, the total time for completing the evacuation (T) should be kept within the time allotted for the Nafrah (T_A).

The different parameters that affect the shuttle-bus transportation system are as follows:

- The interarrival time for buses entering the system (I_T), which is the time interval between bus arrivals in the system. A small interarrival time may appear to speed up the evacuation operation for pilgrims because the entire bus batch size (N) begins doing their job more quickly, however, it may actually lead to traffic jams and causes overload in Arafat bus-stations, as the number of buses exceeds their capacity. Therefore, it's important to maintain a balance between the level of congestion and the rate at which buses enter the route. Using less bus interarrival time causes overload in Arafat bus-stations, as the number of buses exceeds their capacity.

Fig. 2. The path of shuttle-bus from Arafat to Muzdalifa.

- The bus trip time during Nafrah (B_T), which depends on the following parameters:
  - The pilgrims' loading time in Arafat (L_T).
  - The pilgrims' unloading time in Muzdalifa (U_T).
  - The buses' speed (B_S).
- The maximum number of cycles (loops) that each bus completes across the system before departing for the parking area (C_N). Apparently, a higher number of cycles require less bus batch size (N), but bus drivers may be more tired as they spend more time driving.

The following performance metrics can be used to assess the efficiency of shuttle-bus transportation system:

- The number of bus trips reached Muzdalifa (M_N). As mentioned earlier, for each bus trip, a group of fifty pilgrims are evacuated. Therefore, the number of bus trips is considered an indicator of the number of pilgrims that are evacuated. Moreover, another type of city-bus can be utilized, which allows evacuating a group of eighty pilgrims per bus trip.
- Total number of buses exists in the system at a certain time (N_{CB}), which is considered an indicator of the total time for completing the evacuation (T).

Moreover, traffic congestion is taken into consideration for evaluating the transportation system efficiency.

Table I summarizes the parameters used in this work to model the shuttle-bus pilgrims transportation system.

TABLE I. PARAMETERS OF THE SIMULATION MODEL

Parameter	Description
Buses batch size (N)	The overall number of buses dedicated for the transportation of pilgrims.
Nafrah time (T_A)	Time allotted for the Nafrah (the available time to finish the evacuate pilgrims from Arafat to Muzdalifah)
Total evacuation time (T)	Total time for completing the evacuation process
Interarrival time (I_T)	The time interval between bus arrivals in the system.
Bus trip time (B_T)	Total time for a bus to travel from Arafat to Muzdalifah
Loading time (L_T).	Pilgrims' loading time in Arafat
Unloading time (U_T)	Pilgrims' unloading time in Muzdalifa
Bus speed (B_S).	Average speed of a bus during the trip from Arafat to Muzdalifah
Number of cycles (C_N)	The maximum number of cycles (loops) that a bus completes across the system before departing for the parking area
Number of bus trips (M_N)	Total number of bus trips reached Muzdalifa
number of buses (N_{CB})	Total number of buses exists in the system at a certain time

B. Setting up the Model of the Shuttle-Bus System

The first step in the computer modeling operation is the data collection of system specifications, input variables, as well as performance of the existing shuttle-bus system. This is done by observing the actual transportation system performance during Hajj seasons. Based on the actual data collected from the field during Hajj seasons, the values of the following parameters were determined as:

- The interarrival time for buses entering the system (I_T) is 10 seconds. This means that six buses enter the system every minute.
- The number of loading stations in Arafat (L_{SN}) is 80 stations.
- The number of unloading stations in Muzdalifa (U_{SN}) is 32 stations.
- The pilgrims' loading time in Arafat (L_T) was taken as a triangular distribution function as triangular (6, 8, 10), with the min value of 6 min., max value of 10 min., and most likely value of 8 min.
- The pilgrims' unloading time in Muzdalifa (U_T) was taken as a triangular distribution function as triangular (4, 6, 8), with the min value of 4 min., max value of 8 min., and most likely value of 6 min.
- The buses' speed (B_S) was taken as 70 km/h, unless other values are tested.
- The maximum number of loops (C_N) was taken as 6 loops, unless other values are tested.
- The typical time of Nafrah (T_A) is about seven hours.

C. Building the Model of the Shuttle-Bus System

The next step is model construction by developing schematics and network diagrams of the shuttle-bus system, abstracting the essential features of the system, and programming the system operations that characterize the system.

This model architecture was built using Anylogic, which is a multi-method simulation tool with an intuitive GUI. It is completely written in Java and enables combining process modeling, system dynamics and agent-based modeling in one model. Moreover, it has a built-in Road Traffic Library. On one hand, Anylogic seems to be a perfect tool for our research since a microsimulation model of traffic flow can be created directly in Anylogic. On the other hand, several difficulties had to be overcome due to the fact that the tool is not primarily intended for shuttle-bus transportation systems. In order to make sure that the designed model is an accurate representation of the real system, a model validation is performed. This is done by using actual data collected from the field during Hajj seasons. The typical duration of Nafrah is about seven hours.

The model is carried out using an exclusive two-lane bus road. The processes' general structure of the model is shown in Fig. 3. In this modeled environment of roads in Mashaaer Holy Sites (especially Arafat-Muzdalifa area), concurrent groups of simulated agents interact with potential to enable direct acquisition of statistics and indications.

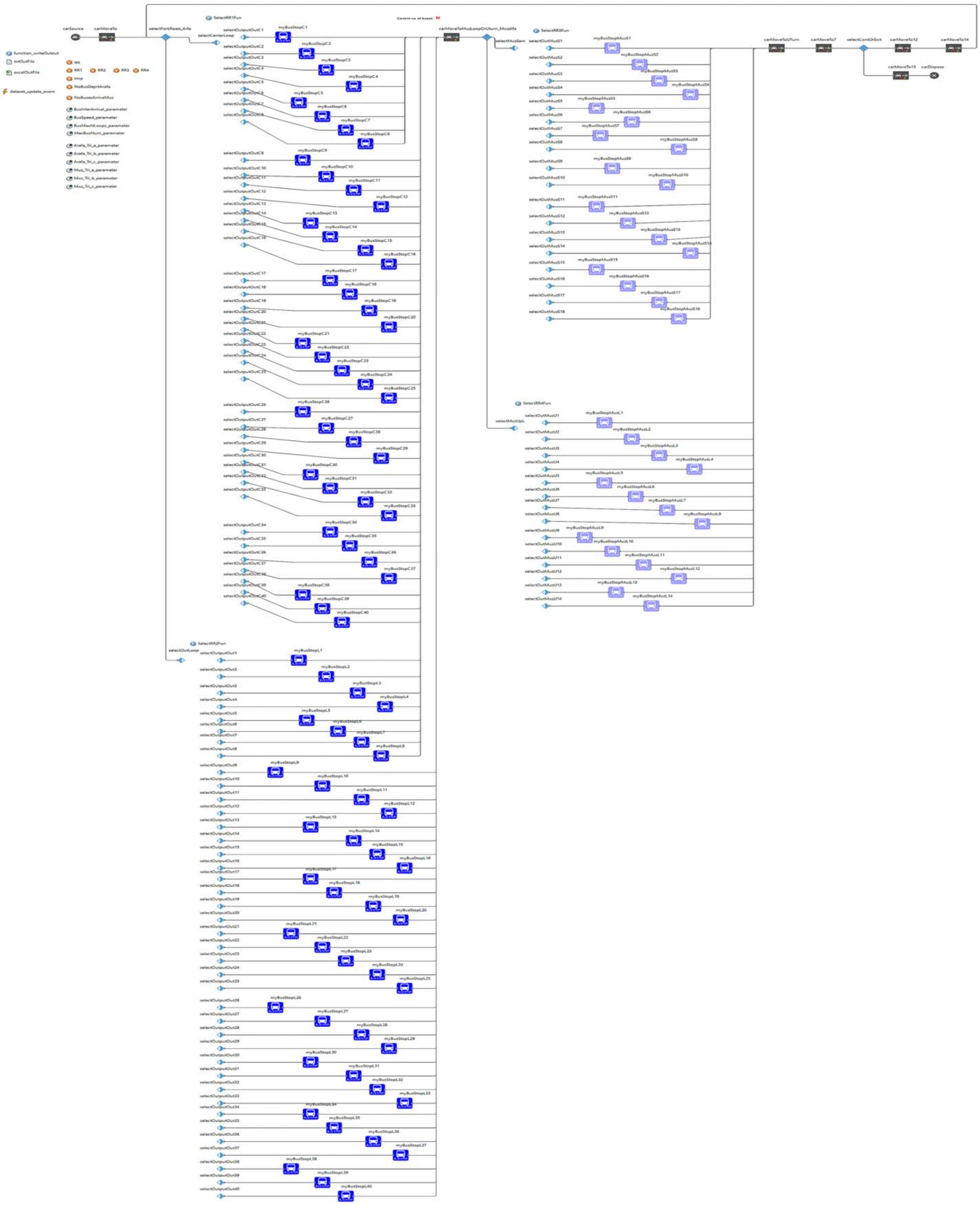


Fig. 3. The processes structure of the model.

The main processes of the model include:

- CarSource: It generates cars (buses) and tries to put them into the specified location inside a road network.
- CarMoveTo: It controls the car movement by calculating the way from its current location to the specified destination.
- SelectOutputIn and SelectOutputOut: For routing agents (buses) to different flowchart branches (bus stations).
- Delay: Delays agents (buses) for a given amount of time.
- CarDispose: Removes a car (bus) from the model.

The system parameters can be controlled through some input-fields in the starting screen of the proposed simulation system. These model parameters include:

- BusInterArrival_parameter: It controls the interarrival time for buses entering the system (in min.).
- Arafa_Tri_a_parameter, Arafa_Tri_b_parameter, and Arafa_Tri_c_parameter: It controls the loading time in Arafat.
- Muz_Tri_a_parameter, Muz_Tri_b_parameter, and Muz_Tri_c_parameter: It controls the unloading time in Muzdalifa.
- BusSpeed_parameter: It controls the speed of a bus.
- BusMaxNLoops_parameter: It controls the maximum number of cycles (loops) that a bus travels before leaving the system.

The simulation screen has some active camera viewports. Examples of the cameras that the system has include:

- Arafat area Cam: A camera that follows the loading bus stations in Arafat site.
- Muzdalifa area Cam: A camera that follows the unloading bus stations in Muzdalifa site.

A screenshot of the simulation screen (at time = 60 min.) is shown in Fig. 4.

D. Validation of the Model of the Shuttle-Bus System

Comes next an important operation, which is model verification. This is to ensure the correctness of the logical structure of the model and the correctness of the represented form in the computer.

In order to make sure that the designed model is an accurate representation of the real system, a model validation is performed. This is done by comparing the results of the simulation model with actual data collected from the field during Hajj seasons.

In the following section, an example of a simulation scenario is shown, which has been used to prove that our model gives realistic results compared to the actual data already collected.

Fig. 4. A screenshot of the simulation screen.

IV. Simulation Results

Through a series of simulations, the model's behavior, and the effects of changing various parameters on the shuttle-bus transportation system are examined. An example of a simulation scenario is provided in this section.

After running the simulation experiment using the aforementioned parameters for a long duration of time, the simulation results were observed. It was found that the average trip time B_T, from Arafat to Muzdalifa, is about 21 min. The total number of buses that existed in the system and the number of trips departed Arafa and arrived Muzdalifa were observed as can be shown in Fig. 5. It can be seen in the figure that using an interarrival time of 10 seconds, the buses batch size (N) increases gradually and reach a number of 700 buses during around 114 min. (point B in the figure). In addition, using this buses batch size, and with a maximum number of loops (C_N) of 6 loops, buses start to depart to the parking area (point C in the figure) after 4 hours and 15 min., hence, the number of buses existed in the system starts to decrease until all buses finish their job. By the time of around eight hours, the number of trips departed Arafa and arrived Muzdalifa was 4200 (point D in the figure), which means that around 210000 pilgrims were successfully evacuated to Muzdalifa, or around 336000 pilgrims were successfully evacuated, when the type of 80-passenger city-bus is used.

In Fig. 6, the results of a simulation experiment that examines the effect of tuning the maximum number of cycles (C_N) are shown. The figure shows the number of trips arriving in Muzdalifa and the total number of buses existing in the system for different number of loops, using a bus batch size N = 600. It can be depicted from the figure that:

- For C_N = 6, a total of 3600 trips (180000 pilgrims, or 288000 when the type of 80-passenger city-bus is used) were able to reach Muzdalifa within 7 hours and 20 minutes. In addition, the total duration for completing the evacuation (whole buses batch were able to leave the system to the parking area) was 7 hours and 42 minutes.
- For C_N = 7, a total of 4200 trips (210000 pilgrims, or 336000 pilgrims when the type of 80-passenger city-bus is used) were able to reach Muzdalifa within 8 hours and 26 minutes. In addition, the total duration for completing the evacuation was 8 hours and 48 minutes.
- For C_N = 8, a total of 4800 trips were able to reach Muzdalifa within 9 hours and 20 minutes. In addition, the total duration for completing the evacuation was 9 hours and 54 minutes.

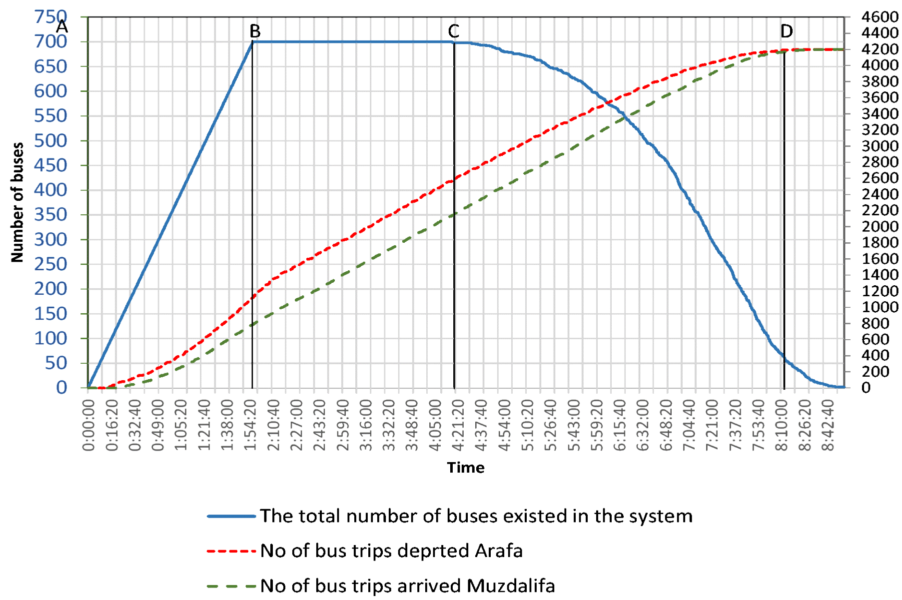
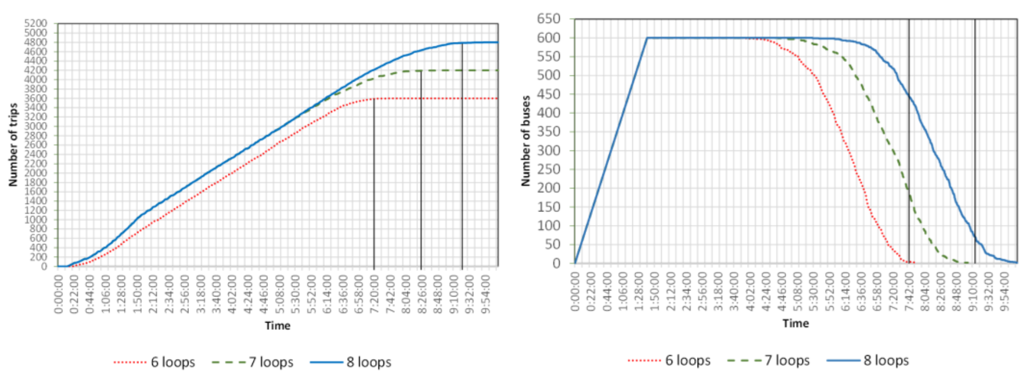


Fig. 5. The total number of buses existed in the system and the number of trips departed Arafa and arrived Muzdalifa for (700 batch of buses and 6 loops).



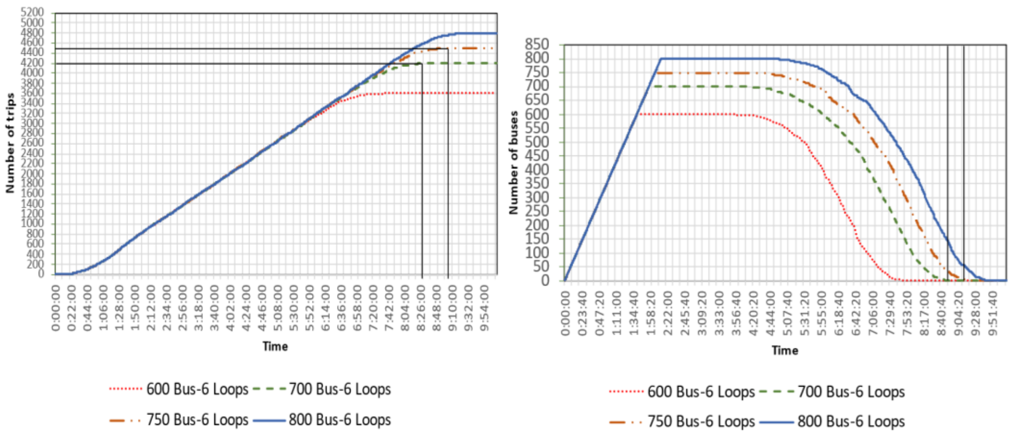
(a) (b)

Fig. 6. The effect of tuning the maximum number of cycles (C_N): (a) The number of trips arrived Muzdalifa for different number of loops; (b) The total number of buses existed in the system for different number of loops.

The results of another simulation experiment that examines the effect of tuning different bus batch sizes (N) are shown in Fig. 7. The figure shows the number of trips arriving in Muzdalifa and the total number of buses existing in the system for different N. It can be depicted from the figure that:

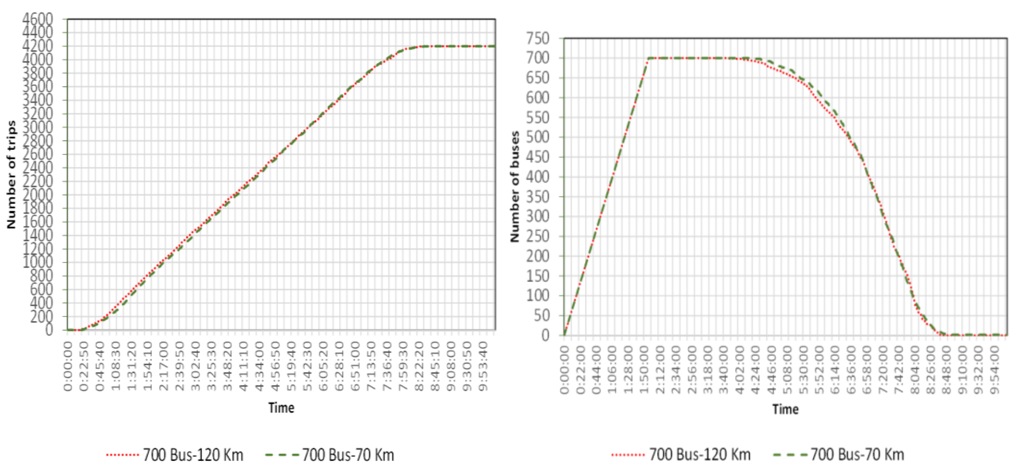
- for N = 600, a total of 3600 trips (180000 pilgrims, or 288000 pilgrims when the type of 80-passenger city-bus is used) were able to reach Muzdalifa within 7 hours and 20 minutes. In addition, the total duration for completing the evacuation (whole buses batch were able to leave the system to the parking area) was 7 hours and 42 minutes.
- for N = 700, a total of 4200 trips (210000 pilgrims, or 336000 pilgrims when the type of 80-passenger city-bus is used) were able to reach Muzdalifa within 8 hours and 26 minutes. In addition, the total duration for completing the evacuation was 8 hours and 48 minutes.
- for N = 750, a total of 4500 trips (225000 pilgrims, or 360000 pilgrims when the type of 80-passenger city-bus is used) were able to reach Muzdalifa within 9 hours. In addition, the total duration for completing the evacuation was 9 hours and 10 minutes.
- for N = 800, a total of 4800 trips (240000 pilgrims, or 384000 pilgrims when the type of 80-passenger city-bus is used) were able to reach Muzdalifa within 9 hours and 32 minutes. In addition, the total duration for completing the evacuation was 9 hours and 40 minutes.

While not always applicable and for the sake of experimenting, buses with faster speed (120 km/h) were tested. The calculated statistics, after running the simulation, are shown in Fig. 8. It can be seen in the figure that increasing the bus speed does not help in increasing the arrival rate in Muzdalifa, as the results are similar to the results when using bus speed of 70 km/h.



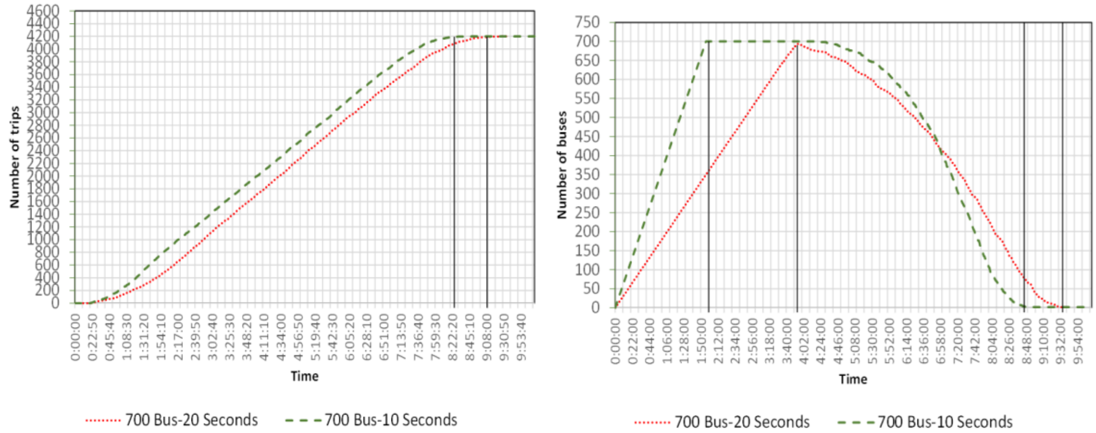
(a) (b)

Fig. 7. The effect of tuning different bus batch sizes (N): (a) The number of trips arrived Muzdalifa for different bus batch sizes; (b) The total number of buses existed in the system for different bus batch sizes.



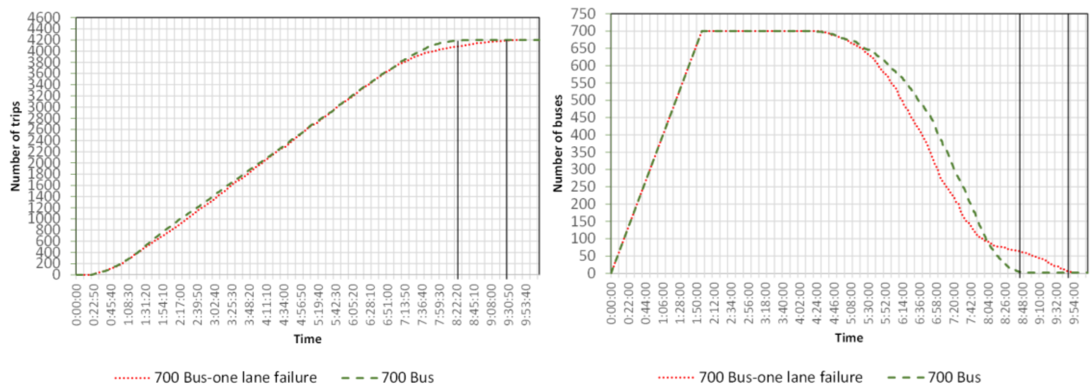
(a) (b)

Fig. 8. The effect of tuning different bus speed (Bs): (a) The number of trips arrived Muzdalifa for different bus speed; (b) The total number of buses existed in the system for different bus speed.



(a) (b)

Fig. 9. The effect of tuning the interarrival time for buses entering the system (IT): (a) The number of trips arrived Muzdalifa for different Bus interarrival times; (b) The total number of buses existed in the system for different Bus interarrival times.



(a) (b)

Fig. 10. The impact of a failure that might occur in one of the road lanes: (a) The number of trips arriving in Muzdalifa; (b) The total number of buses existing in the system.

The results of another simulation experiment that examines the effect of tuning the interarrival time for buses entering the system (I_T), are shown in Fig. 9. It can be seen in this figure that using I_T = 10 seconds, the buses batch size (700) increases gradually and reach a number of 700 buses during around 114 min, and after 4 hours and 15 min., buses start to depart to the parking area. On the other hand, using I_T = 20 seconds, the buses batch size (700) increases gradually and reach a number of 700 buses during around 3 hours and 55 min. and at that time buses start to depart to the parking area, as several buses have already reached the maximum number of cycles. The results of the simulation showed that using I_T = 10 seconds was a suitable choice as it maintains a good balance between the level of roads congestion and the rate at which buses enter the route.

Fig. 10 depicts the results of another simulation experiment that investigates the impact of a failure that might occur in one of the road lanes. The figure depicts the number of trips arriving Muzdalifa and the total number of buses in the system in two scenarios: a scenario with no failure and another scenario with one-lane failure. The figure shows that the presence of one-lane failure causes a slight delay in the movement of the buses. However, the delay is minor because using dedicated roads for traffic helps to keep the level of congestion low.

V. Optimization of the Shuttle-Bus Transportation System in Arafat-Muzdalifa Area

In the optimization process, the results of simulation experiments that include all possible combinations of parameters are registered. As mentioned earlier, the parameters include:

- the overall number of buses dedicated for the transportation of pilgrims (N),
- the maximum number of cycles (loops) that each bus completes across the system before departing for the parking area (C_N),
- the total amount of time for completing the evacuation that all buses spend in the system before departing for the parking area (T), and
- The total number of bus trips that reach Muzdalifa (N_{Trips}).

The objective of our optimization problem is to determine the optimal solution with respect to one or more of the above parameters. This could be the minimum N, the minimum C_N, the minimum T, or the maximum (N_{Trips}). In general, N_{Trips} = N * C_N; hence, maximizing N_{Trips} while minimizing N indicates that C_N must be maximized.

The objective function can be formulated as $\min_{(N,C_N,T,N_{Trips})} S_\omega$, where S_ω is a weighted function that includes the system parameters. This function can be re-written as a weighted function of the parameters as:

$$S_\omega = \omega_1 N + \omega_2 C_N + \omega_3 T + \omega_4 \frac{1}{N_{Trips}} \quad (1)$$

However, the values of the system parameters in the above equation are not within close ranges. Therefore, to have a consistent formula for S_ω , the system parameters in the equation are normalized by dividing each one by its possible maximum value. Such maximum values are clearly determined from the set of all possible combination of parameters that are used in the simulation experiments. Hence, a normalized parameter is obtained as

$$\hat{p} = p/p_{Max}\,, \quad (2)$$

where, p is a parameter value, $\hat{p}$ is a normalized parameter value, and p_{Max} is the maximum possible value of the parameter. The weighted summation function in Eq. (1) is, therefore, reformulated as,

$$S_\omega = \omega_1 \hat{N} + \omega_2 \widehat{C_N} + \omega_3 \hat{T} + \omega_4 \widehat{\frac{1}{N_{Trips}}} \quad (3)$$

To be accepted as a possible solution, the obtained parameters shouldn't exceed predefined limits (the available number of buses, the maximum number of cycles, and the target time for completing the evacuation). In addition, the target number of bus trips that reach Muzdalifa should be satisfied. In the considered system (the shuttle-bus transportation system for pilgrims on the route from Arafat to Muzdalifa (Nafrah)), the parameters are determined using a range of (500 to 850) for N, a range of (3 to 8) for CN, and a range of (1500 to 6800) for NTrips. Table II illustrates the targeted values of the system parameters.

An excerpt of the outcomes from simulation experiments that looked at every possible combination of parameters is shown in Table III.

Eq. (3) can be used either to optimize one parameter or to find an optimal solution with respect to more than one parameter. In the former case, the weight of the targeted parameter is set to 1, while the weights of the other parameters are set to 0. In the latter case, the weights of the selected parameters are set to 1, while the other weights are set to 0. The following experiments illustrate how different sets of weights are used for the optimization process:

- For the maximum number of buses (N), the weights are set to the values of ($\omega_1 = 1$, $\omega_2 = 0$, $\omega_3 = 0$, $\omega_4 = 0$), hence, only the effect of $\hat{N}$ is considered in S_ω. The optimized result of S_ω in this case is 0.59. This optimized result gives a number of possible solutions. The best of them in terms of total evacuation time gives the following values: N=500, C_N = 4, N_{Trips} = 2000, T = 294.92 min. However, this solution is not an acceptable as it doesn't satisfy the target number of bus trips that reach Muzdalifa. The best solution that complies with the predefined limits has the following values: N=500, C_N = 6, N_{Trips} = 3000, which results in a total time (T) of 395.87 min.
- When the optimization process is performed to fine the minimum number of cycles (C_N), the weights are set to the values of ($\omega_1 = 0$, $\omega_2 = 1$, $\omega_3 = 0$, $\omega_4 = 0$), where the effect of $\widehat{C_N}$ is only considered in S_ω. The optimized parameters, in this case, were determined as N=500, C_N = 3, N_{Trips} = 1500, and the total amount of time for completing the evacuation (T) was found to be 240.27 min. Although this solution minimizes the number of cycles, this is not an acceptable solution as it doesn't satisfy the target number of bus trips that reach Muzdalifa. The first solution that complies with the predefined limits has the following values: N=720, C_N = 4, N_{Trips} = 2880, which results in a total time T of 378.88 min.
- To minimize the total amount of time for the evacuation process (T), the weights are set to the values of ($\omega_1 = 0$, $\omega_2 = 0$, $\omega_3 = 1$, $\omega_4 = 0$), which means only the effect of $\hat{T}$ is considered in S_ω.

TABLE II. THE TARGETED VALUES OF THE SYSTEM PARAMETERS

N	≤ 800 buses
C_N	≤ 8 cycles
T	≤ 480 min.
N_{Trips}	≥ 2820 (around 225600 pilgrims, when 80-passenger city-bus is used)

TABLE III. AN EXCERPT OF THE SIMULATION EXPERIMENTS RESULTS

N	C_N	T	N_{Trips}	$1/N_{Trips}$	$\hat{N}$	$\widehat{C_N}$	$\hat{T}$	$\widehat{1/N_{Trips}}$
500	4	294.92	2000	0.000500	0.59	0.50	0.37	0.75
510	4	298.44	2040	0.000490	0.60	0.50	0.37	0.74
530	4	302.33	2120	0.000472	0.62	0.50	0.38	0.71
520	4	314.95	2080	0.000481	0.61	0.50	0.39	0.72
500	5	356.44	2500	0.000400	0.59	0.63	0.44	0.60
500	3	240.28	1500	0.000667	0.59	0.38	0.30	1.00
510	3	242.13	1530	0.000654	0.60	0.38	0.30	0.98
540	4	319.03	2160	0.000463	0.64	0.50	0.40	0.69
520	3	248.80	1560	0.000641	0.61	0.38	0.31	0.96
510	5	366.51	2550	0.000392	0.60	0.63	0.46	0.59
530	3	251.00	1590	0.000629	0.62	0.38	0.31	0.94
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

- In this case, the optimal solution gives the values of N=500, C_N = 3, N_{Trips} = 1500. The total amount of time for completing the evacuation (T) in this case was found to be 240.27 min. Although this solution resulted in the minimum time, the solution is not acceptable because it doesn't satisfy the target number of bus trips that reach Muzdalifa. The first solution that complies with the predefined limits has the following values: N=720, C_N = 4, N_{Trips} = 2880, which results in a total time T of 378.88 min.

- To satisfy the target number of bus trips (N_{Trips}), a possible scenario is to find the maximum N_{Trips}. Here, the weights are set to the values of ($\omega_1 = 0$, $\omega_2 = 0$, $\omega_3 = 0$, $\omega_4 = 1$), to allow the effect of $\widehat{\frac{1}{N_{Trips}}}$ to be only considered in S_ω. The results of this case were determined as N=850, C_N = 8, N_{Trips} = 6800, in which the total amount of time for completing the evacuation (T) was found to be 801.30 min. Although this solution achieves a large number of bus trips that reach Muzdalifa, it consumes lots of resources, in terms of the number of buses dedicated for the transportation of pilgrims (N), in addition to the maximum number of cycles (loops) that each bus completes across the system. Moreover, the required time for completing the evacuation is long. Hence, this is not an acceptable solution. The first solution that complies with predefined limits has the following values: N=750, C_N = 5, N_{Trips} = 3750, which results in a total time T of 476.75 min.

In order to maintain the effects of all parameters, the weights are set to the values of ($\omega_1 = 1$, $\omega_2 = 0$, $\omega_3 = 1$, $\omega_4 = 1$). The reason for having the value $\omega_2 = 0$ is to solve the contradiction in (4), by omitting the effect of C_N. The optimized parameters, in this case were determined as N=500, C_N = 6, N_{Trips} = 3000, and with these parameters the total amount of time for completing the evacuation (T) was found to be 395.87 min. This can be considered as an accepted solution that achieves the targets while maintaining the system resources within the available limits.

Table IV summarizes the results of the above experiments.

In fact, the values of weights used in Eq. (3) can be chosen to define the significance of each parameter in S_ω. In our experiments, we used equal weights to indicate equal importance of the parameters. However, unequal values of weights will give some parameters more importance than others.

TABLE IV. A SUMMARY OF THE EXPERIMENTS ILLUSTRATING EFFECTS OF VARYING THE WEIGHTS IN THE OPTIMIZATION PROCESS

weights	N	C_N	T	N_{Trips}
$\omega_1 = 1, \omega_2 = 0, \omega_3 = 0, \omega_4 = 0$	500	6	395.87	3000
$\omega_1 = 0, \omega_2 = 1, \omega_3 = 0, \omega_4 = 0$	720	4	378.88	2880
$\omega_1 = 0, \omega_2 = 0, \omega_3 = 1, \omega_4 = 0$	720	4	378.88	2880
$\omega_1 = 0, \omega_2 = 0, \omega_3 = 0, \omega_4 = 1$	750	5	476.75	3750
$\omega_1 = 1, \omega_2 = 0, \omega_3 = 1, \omega_4 = 1$	500	6	395.87	3000

VI. CONCLUSIONS

In this paper, a computer modeling of pilgrims' shuttle-bus transportation system in Mashaaer Holy Sites, were presented. The model was designed using a multimodal modeling and simulation tool developed by AnyLogic to include operations during the pilgrims' transport from Arafat to Muzdalifa via shuttle-buses. The proposed model can be used for optimizing the pilgrim's transportation system with respect to different parameters since the results of the simulation may be used to assess the effectiveness of the current system and to suggest changes that might be made. In our experiments, we used equal weights to indicate equal importance of the parameters. In future work, unequal values of weights of parameters can be set to give more importance of some parameters than others. In addition, this paper focused on one of the paths of the hajj shuttle bus system. As a future work, the simulation model may be extended to include other paths.

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