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A PROPOSED SIMULATION MODEL FOR OPTIMIZING THE TRAFFIC FLOW FROM ARAFAT TO MUZDALIFAH

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ABSTRACT: *This project simulates the flow of pilgrims when they travel from Arafat to Muzdalifah. The system includes a road network that connects Arafat to Muzdalifah. It is represented as a queuing system with different queue measurements that simulate reality. The system includes various types of transportation, such as small and large buses and trains, which are represented by objects with different lengths and colors. Some individuals choose walking over modern means of transportation, so pedestrians are also represented. All of the system objects carry specifications about their corresponding source system's objects; these specifications are data collected by the Ministry of Hajj. The primary objective of the system is to answer scenario questions to support decision-making in optimizing Hajj traffic, which can be achieved by manipulating the system's variables and observing the key performance indicators of the system. The system presents the experiment's results as visual feedback alongside written reports with statistics.*

KEYWORDS: Hajj Simulation, Traffic Flow, Arafat, Muzdalifah

INTRODUCTION

Pilgrimage, or the Hajj, is the 5th pillar of Islam. Every adult Muslim around the world must perform it at least once in their lifetime. Due to the massive number of pilgrims arriving every year, the crowds and traffic congestion are enormous near the Hajj holy places. These crowds and traffic congestion can cause series problems, such as the late arrival of pilgrims to their destinations. In addition, there is inefficiency in the providing of timely essential services, such as medical care, in case of emergencies.

The Saudi government, represented by the Ministry of Al-Hajj, spends billions of Riyals in establishing different projects to decrease the negative impact to make the Hajj easier and smoother for pilgrims. These ambitious and helpful projects include building bridges, digging tunnels, and broadening roads.

The pilgrims in general are divided into local pilgrims and abroad pilgrims. The local pilgrims, in addition to some abroad pilgrims, use the train lines network. The abroad pilgrims are divided into six categories: Non-Arabic Africa, Iran, Southeast Asia, South Asia, Turkey, and Arabian pilgrims. Each category of pilgrim has a road network, sometimes shared with another category. The road networks are interrelated and very complex. This paper focuses only on non-Arabic African pilgrims' roads, with consideration of Iranian pilgrims that share the same road network. These two establishments use the shuttle-trips transportation system.

This research aims to build a simulator that will test the optimization of the working system.

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Problem Definition

The simulation model will study the non-Arabic African pilgrims' flow through the shuttle-trips transportation system. The model will show how well the system is optimized and how well the system is utilizing its resources. In addition, it tests alternative scenarios, decides on the most optimized option, and provides a list of justifications.

Developing a simulation model for the non-Arabic African shuttle-trips system is intended to support the decision-making process in working toward a more optimized system performance.

METHODOLOGY

The methodology used in building our simulation model is called the "M&S life-cycle management framework" (Choi & Kang, 2013). It is a qualitative software development methodology, since it aims to increase the quality of the source system by obtaining an in-depth understanding of the traffic behavior. In addition, it investigates the why and how of decision-making, not just what, where, and when. Moreover, it produces information and conclusions only on particular case studies. This specific framework was chosen because it is a well-known methodology within the discrete event simulation (DES) research area, and will promote the achievement of the project's aims and objectives. Any data necessary to develop the project will be collected from the Ministry of Al-Hajj. As shown in Figure 1 (Choi & Kang, 2013), the methodology consists of the following steps:

1. Identify the problem: diagnose and analyze of the Hajj environment in order to identify the source system, the problem definition, and the objectives of the study.
2. Specify experimental frames: to observe the hajj system.
3. Describe and qualify the model: to build the reference model to be consistent with observed behavior and data to ensure the model is fit for purpose.
4. Build the formal model and validate the model: the formal model will be the state transition diagram that is based on finite state machine (FSM). The validation will be done by comparing the model's performance under the system variables in line with the performance of the Hajj system.
5. Implement the simulator, experiment, and verify it: the model will be implemented using a simulation software tool, and it will be experimented with different suggested scenarios.
6. Calibrate the model: to achieve high credibility for the model.
7. Draw conclusions: to support decision-making and the taking of further actions in the traffic flow of vehicles.

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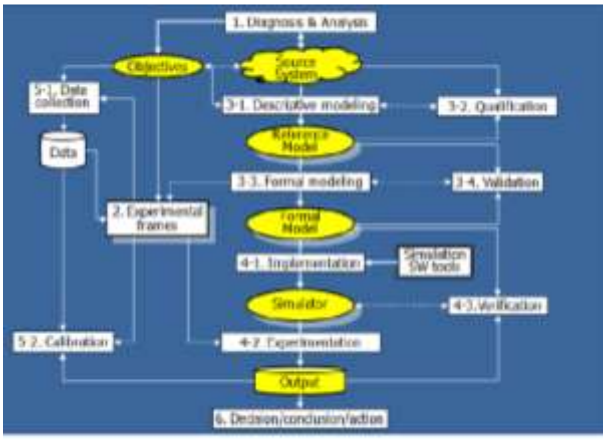

Figure 1: M&S Life-cycle management framework

Source: Choi & Kang (2013, p. 26)

Tools

From among the various tools that are often used for modeling and simulation such as 20-sim, Arena, Modsim, Promodel, Prosolvia and many other products, we choose Arena, which is a well-known simulation software package that consists of an optimization system and has the ability to draw visuals.

LITERATURE REVIEW

Prior to modern times, simulators were designed manually, but now computers are used affectively to design simulators, making them more valid and reliable. Technology has made everything faster and easier, saving time and effort.

Simulation modeling is the process of creating and analyzing a digital prototype of a physical model to predict its performance in the real world. Simulation modeling is used to help designers and engineers understand whether, under what conditions, and in which ways a part could fail and what loads it can withstand. Simulation modeling can also help predict fluid flow and heat transfer patterns (Winsberg, 2001).

Domain Description

Hajj is considered the largest gathering of human beings in the world in a specific and limited time and space. Typically, the total number of pilgrims is 2.5 million; 1 million of these pilgrims come from outside the kingdom of Saudi Arabia (Central Hajj Committee).

In the ninth of Dhu al-Hijjah, at sunset, pilgrims start traveling from Arafat to Muzdalifah. Foreign pilgrims use the shuttle-trips system for traveling. They are divided into geographical groups (East Asia pilgrims, the non-Arab African pilgrims, etc.) and each group is assigned to one road out of the eight that are dedicated for shuttle trips. The Iranian and the non-Arab African pilgrims use the same road.

At sunset, buses start leaving the parking area in groups. Each group contains a pre-determined number of buses with a pre-determined delay time between the groups leaving the parking area

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to avoid traffic jams. For example, African buses are divided into 12 groups. Each group has 32 buses. The delay time between the groups leaving is five minutes.

Each institution is divided into a number of camps. Each camp has from one to three gates. Fifty pilgrims wait at the gates for the buses to arrive. It takes an average of 10 minutes to load the buses at Arafat, and 45 minutes roundtrip, plus unload time at Muzdalifah. The shuttle trips continue until all pilgrims are transferred to Muzdalifah.

Figure 2 shows the holy sites map that illustrates the African and Iranian establishments' road network and locations. The red area indicates the African establishment and the blue area indicates the Iranian establishment. The two establishments – African and Iranian – share the same road network. Therefore, our simulation model covers both of them.

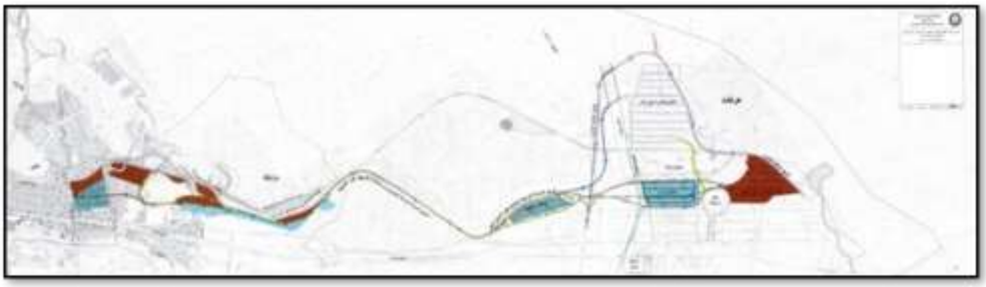

Figure 2: African and Iranian establishment road network

Modelling and Simulation

Modeling is the process of producing a model that is a representation of the construction and workings of a system of interest. Computer simulation is the discipline of designing a model of a system, executing the model on a digital computer, and analyzing the execution output (Choi & Kang, 2013). The terms "computer simulation" and "modeling & simulation" are used interchangeably. A simulation of a system is the operation of a model of the system. It is a tool to evaluate the performance of an existing or proposed system under different configurations of interest and over long periods of real time. Usually, it is too expensive or impractical to perform this analysis within the physical system that the model represents (Maria, 1997).

There are two major types of simulation: continuous systems and discrete event systems. Continuous simulation is a numerical evaluation of a computer model of a physical dynamic system. It's like flight and weather simulators, attempt to quantify the changes in a system continuously over time in response to controls. DES is a computer evaluation of discrete-event dynamic system model where the operation of the system is represented as a chronological sequence of events. State-based modeling is used to describe the internal and external transition functions. (Choi & Kang, 2013).

Discrete event simulation is less detailed (the smallest time unit is larger) than continuous simulation, but it is much simpler to implement, so it is used in a wide variety of situations (Choi & Kang, 2013). In this research study, the system is considered a discrete event simulation system.

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Traffic Flow Modeling

The study of traffic flow is concerned with understanding and assisting in the prevention of and remedy to traffic congestion problems (May, 1990). The first attempts to develop a mathematical theory for traffic flow date back to the 1930s (Greenshields; Adams, 1935). However, even today we lack a satisfactory and general mathematical theory to describe real traffic flow conditions. This is because traffic phenomena are complex and nonlinear, and depend on the interactions of a large number of vehicles and the psychological reactions of human drivers.

Traffic flow models can be grouped into three main categories depending on the level of detail (Adam; Maerivoet & Moor, 2005): microscopic, mesoscopic, and macroscopic. The microscopic models deliver estimated, reliable, and detailed information about the behavior of each single vehicle. The model details separate units with characteristics such as speed, acceleration, and individual driver-vehicle interactions. Microscopic models may be classified in different types based on the so-called car-following modeling approach. The car-following modeling approach implies that the driver adjusts his or her acceleration according to the conditions of leading vehicles. For this reason, microscopic models can be applied to narrow-range transportation systems with a much higher level of detail (Maciejewski, 2010; Papageoriou, Damianou, & Pitsilides, 2009).

The mesoscopic model requires a moderate depth of detail. It specifies the behavior of individuals in probabilistic or statistical terms.

At the macroscopic level, the analogy with fluid dynamics models is used, with a system of partial differential equations that involves variables such density, speed, and flow rate of a traffic stream with respect to time and space. Macroscopic models apply when detailed information about the behavior of a single vehicle is not required, but rather only a general evaluation of traffic flows in a network is needed. These models are often used for regional transportation planning (Maciejewski, 2010; Papageoriou, Damianou, & Pitsilides, 2009).

The next two sections discuss macroscopic and mesoscopic modeling, since they are the best suited for this project.

Traffic Macroscopic Modeling

In macroscopic simulation, the roadway is divided into discrete segments and time is divided into short time intervals (Derek & Qiu, 2012). Each road segment is a homogeneous unit in which the number of lanes must remain unchanged. On-ramps and off-ramps are always located at the beginnings and ends of the segments, respectively. The concept of road segment index (i) and the state variables density (p), speed (v), and flow (q) are illustrated in Figure 3.

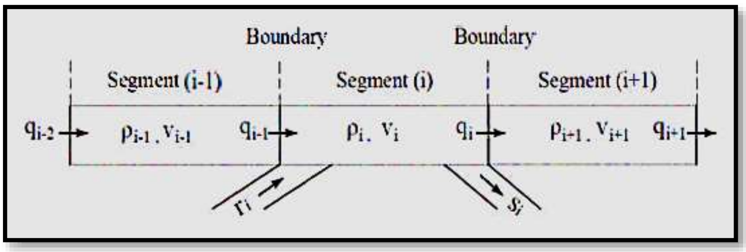

Figure 3: Discretization of a roadway section. Source: Derek and Qiu (2012)

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In order to model jammed traffic properly, two important aspects should be included in the model: boundary conditions and capacity drop. Boundary conditions bring constraints as to how many vehicles from an upstream segment can flow into the immediate downstream segment under various traffic states. To address capacity drop, two capacities should be applied: the capacity from free flow to congested flow and the recovery from congestion. The capacity drop can be incorporated in macroscopic simulation by adding a constraint on the capacity based on the traffic state change. Boundary conditions and capacity drop are written as:

$$q_{i-1}(k) = \min\{[\rho_{i-1}(k)\cdot v_{i-1}(k) + r_i(k) - s_i(k)], Q_i, \frac{[\rho_i(k)\cdot v_i(k) - \rho_{i-1}(k)\cdot v_{i-1}(k)]}{[\rho_i(k) - \rho_{i-1}(k)]}[\rho_m - \rho_i(k)]\}$$

$$q_i(k) = \min\{[\rho_i(k)\cdot v_i(k) + r_{i+1}(k) - s_{i+1}(k)], Q_{i+1}, \frac{[\rho_{i+1}(k)\cdot v_{i+1}(k) - \rho_i(k)\cdot v_i(k)]}{[\rho_{i+1}(k) - \rho_i(k)]}[\rho_m - \rho_{i+1}(k)]\}$$

where ri(k), si(k) is on-ramp and off-ramp flow in segment i at time index k. Each equation above has three terms in the brackets on the right-hand side: the outflow from the immediate upstream segment, the normal capacity of a segment (Qi or Qi+1), and the available space in the current segment, which includes the impact of shockwave from the immediate downstream segment.

For recovery from breakdown, $P_{cr}<P_i(k)$ and $v_i(k)\leq V_{rnin}$:

$$q_i(k+1) = \min[(1-\phi)\cdot \rho_{cr}\cdot v_f, \rho_i(k)\cdot v_i(k)]$$

where P_{cr} - critical density - is the maximum traffic density at which the free flow can be maintained and the traffic flow reaches the capacity. Φ is the rate of capacity drop in percentage. V_{rnin} is the minimum speed in the traffic flow. Both Φ and V_{rnin} are parameters that need to be identified in model calibration (Derek & Qiu, 2012).

Traffic Mesoscopic Modeling

Mesoscopic models can take on various forms (Burghout, 2005). One such form is vehicles grouped into packets that are routed through the network. The packet of vehicles acts as one entity, and its speed on each road (called a link) is derived from a speed density function defined for that link and the density on the link at the moment of entry. The density on a link is the number of vehicles per kilometer, per lane. A speed-density function relates the speed of vehicles on the link to the density. If there is a lot of traffic on the link (the density is high), the speed-density function will give a low speed to the vehicles, whereas a low density will result in high speeds. The lane changes and acceleration/deceleration of vehicles is not modeled.

Another feature of mesoscopic modeling is that individual vehicles are grouped into cells that control their behavior. The cells traverse the link and vehicles can enter and leave cells when needed, but not overtake it. The speed of the vehicles is determined by the cell, not the individual drivers' decisions (Burghout, 2005).

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Alternatively, a queue-server approach is used in some models, where the roadway is modeled as a queuing and a running part. The lanes can be modeled individually, but usually they are not. Although the vehicles are represented individually and maintain their individual speeds, their behavior is not modeled in detail. The vehicles traverse the running part of the roadway with a speed that is determined using a macroscopic speed-density function, and at the downstream end, a queue-server transfers the vehicles to connecting roads (Burghout, 2005).

Modeling Components

Figure 4 illustrates a simplified version behavior of the system

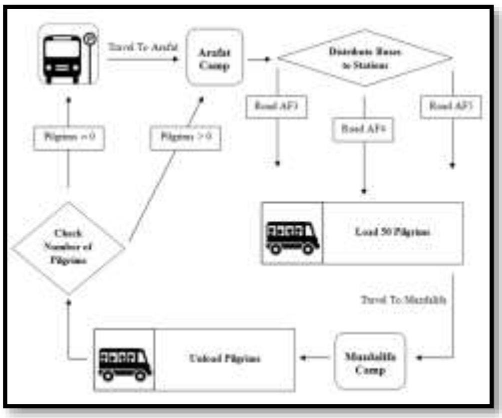

Figure 4: Reference Model Diagram

The system dynamics are described in terms of the activities of the active resources and entities in the DES. The modeling components in this simulation are:

- Entities: African bus and Iranian bus.
- Resources: stations, roads, intersections.
- Activities: traveling, loading, unloading, passing, fixing bus failure.
- Variables: stations state (idle/busy), roads state (idle/busy), intersections state (idle/busy).
- Events: Arrive, Load, Unload, Pass, Failure.

Identifying Entities

All possible paths the entity may take through the system is listed below:

- Exit Parking → Arrive to Arafat → Enter Road (AF3, AF4, or AF5) → Load→ Arrive to Muzdalifah → Unload→ Check Number of Pilgrims → Terminate
- Exit Parking → Arrive to Arafat → Enter Road AF3 → Load → Arrive to Muzdalifah → Unload → Check Number of Pilgrims → Return to Arafat
- Exit Parking → Arrive to Arafat → Enter Road AF3 → Load → Arrive to Muzdalifah → Bus Failure → Fix Bus

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- Exit Parking → Arrive to Arafat → Enter Road AF3 → Load → Arrive to Muzdalifah → Bus Failure → Send Backup Request

Data Flow Diagram

A data flow diagram (DFD) is a graphical representation of the flow of data through an information system, modeling its process aspects. Often DFDs are a preliminary step used in creating an overview of the system that can later be elaborated on. Figure 5 is a simple DFD of this project's source system.

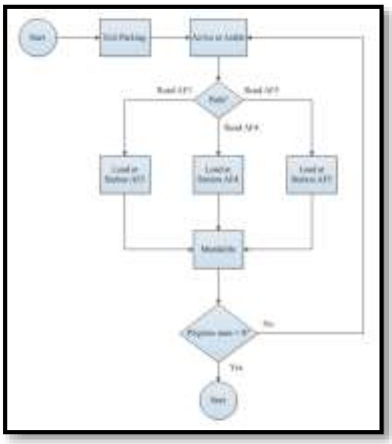

Figure 5: Data Flow Diagram

Source System Overview

This project uses graphical simulation to simulate the flow of the non-Arabic African shuttle-trips system when moving pilgrims from Arafat to Muzdalifah. The system includes a road network that connects Arafat to Muzdalifah. The network is represented as resources with different capacities that simulate reality. Other resources are intersections and loading and unloading stations. The entity flowing through the system is the buses. These buses carry specifications (e.g., speed and capacity) collected by the ministry of Hajj. The system objective is to answer scenario questions, which can be achieved by manipulating the system's variables and then observing the impact on the system. The system presents the results as visual feedback alongside written reports with statistics.

Discrete-Event System Modeling Formalisms

Modeling formalisms are "a well-defined set of graphical conventions for specifying a discrete event simulation system (DES) that has semantics" (Choi & Kang, 2013). They are grouped into four modeling formalisms (Choi & Kang, 2013):

1. Activity-based formalism (from the flow diagram method)

   The dynamics of the system are described in terms of the activities of the active resources and entities in the system using activity cycle diagram (ACD). It turned out that the classical ACD had some inherent limitations in handling complex systems. In order to enhance modeling power and convenience, the concepts of hierarchical ACD and extended ACD were proposed.

2. Process-oriented simulation language and entity flow diagram

The previous modeling formalism becomes an entity-based modeling formalism if only the activities of the entities in the system are considered. The time-ordered sequence of events is the flow of entities, and the diagram of the activity sequence is called an entity-flow diagram. The entity-based modeling formalism has also been adopted in many of the modern simulation languages, including Arena.

3. Event-based formalism (from event scheduling languages)

The system is modeled by defining the changes that occur at event times. Its dynamics are described using an event graph, where the events are represented as vertices and the relationships between events are represented as directed arcs. Event graph models are very compact and they are able to model any system that can be implemented on a modern computer. An example of this modeling formalism language is SIGMA.

4. State-based formalism (from the state transition diagram)

The dynamics of the system are described in terms of the states of the resources within it. The state-based modeling method originated from the classical finite state machine (FSM) used for modeling the behavior of sequential circuits as a state transition diagram. The graphical representation of timed automata (or timer-embedded FSM) is referred to as a state graph. A state graph is composed of a set of state transition diagrams, one for each resource in the system, and the object interaction diagram, which denotes interactions among the objects or the resources in the system.

Among the modeling formalisms described, the most suitable modeling for this traffic simulator is the state-based simulation formalism, since the model can be expressed as an FSM that has many states, where the next state is determined by the current state and the transition (or the action).

CONCLUSION

In this paper, a project was described which aims to support the decision-makers in the Ministry of Al-Hajj by developing a simulation model of the African and Iranian pilgrims traveling from Arafat to Muzdalifah using a shuttle-trips system. The simulation model design discussion provided an overview of the system. The four modeling formalisms were stated and then the state-based diagram was chosen from among them for the Hajj traffic simulation.

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